Supplement to the 2009 Decadal Review

31 July 09

International X-Ray Observatory (IXO) Segmented Glass Flight Mirror Assembly (FMA) Concept Study

Mike Hill / NASA

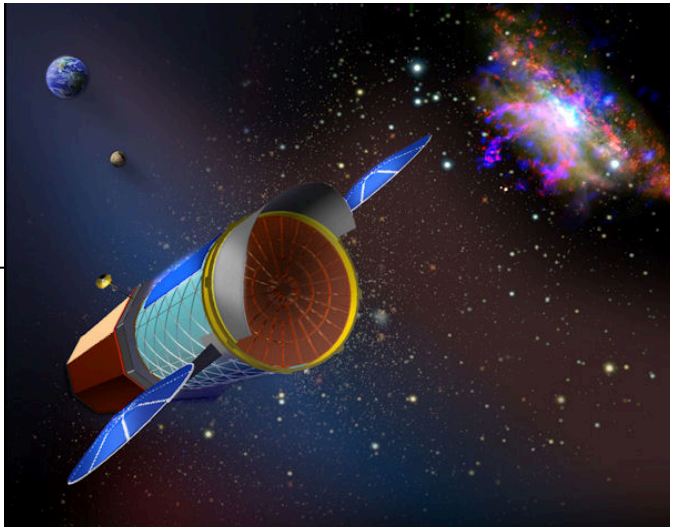


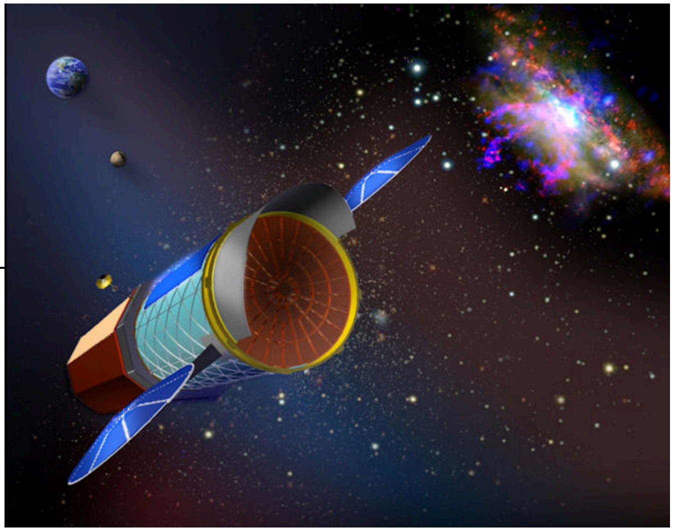
Table of Contents

Page No.

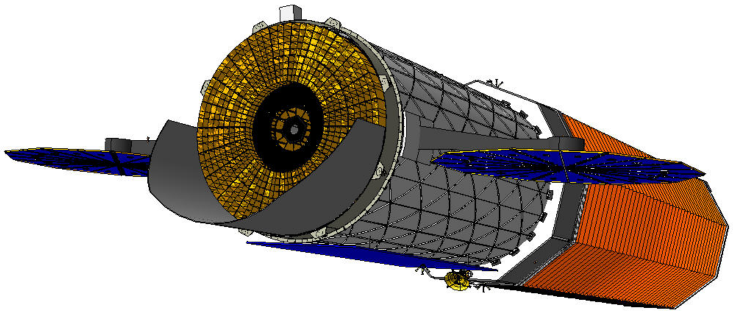
Summary of Flight Mirror Assembly (FMA) Concept Study

- **The FMA Concept Study was started in April 2009**
- **As a result of this study, the following have been accomplished:**
  - **We have derived detailed FMA requirements from the IXO observatory requirements**
  - **We have arrived at a reference/preliminary design for the FMA that meets all these requirements: mass and power allocations, optical design, launch environment, structural and thermal distortion, etc.**
  - **We have clearly identified the technical areas that need development to meet the angular resolution requirement**
  - **We have developed a detailed roadmap to reach TRL 6 by 2012**
  - **We have developed a detailed FMA schedule and I&T plan**
  - **We have developed a grassroots cost estimate and a PRICE-H cost estimate**
- **This document will provide an overview of the key aspects of this concept study**

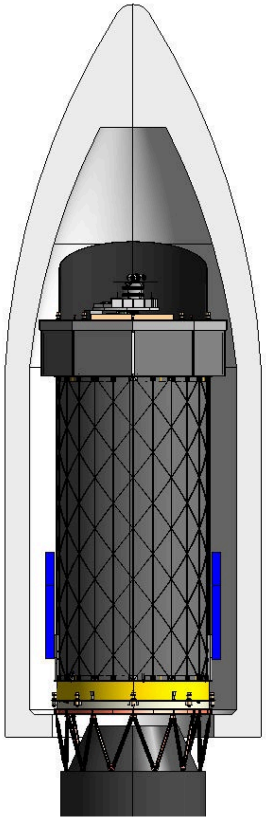
IXO Mission and Flight Mirror Assembly (FMA) Overview



IXO Mission Overview

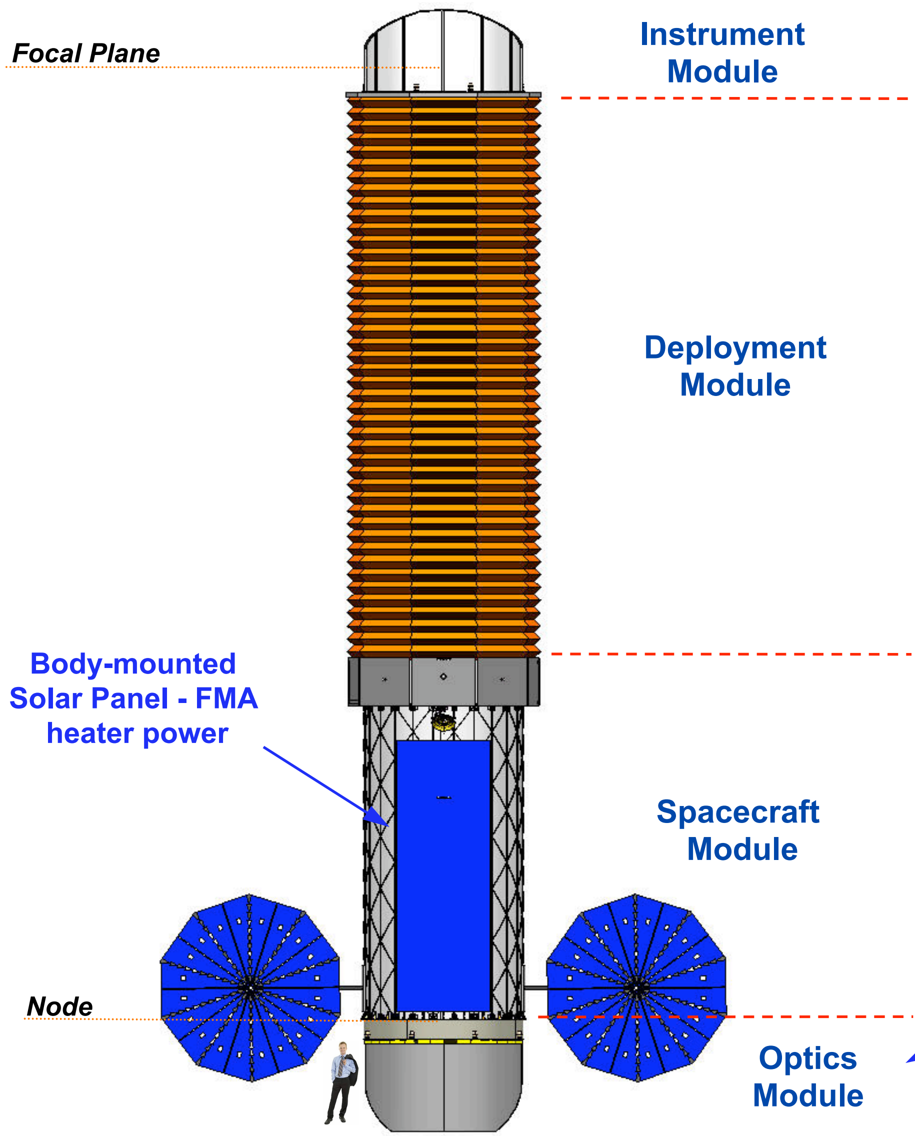


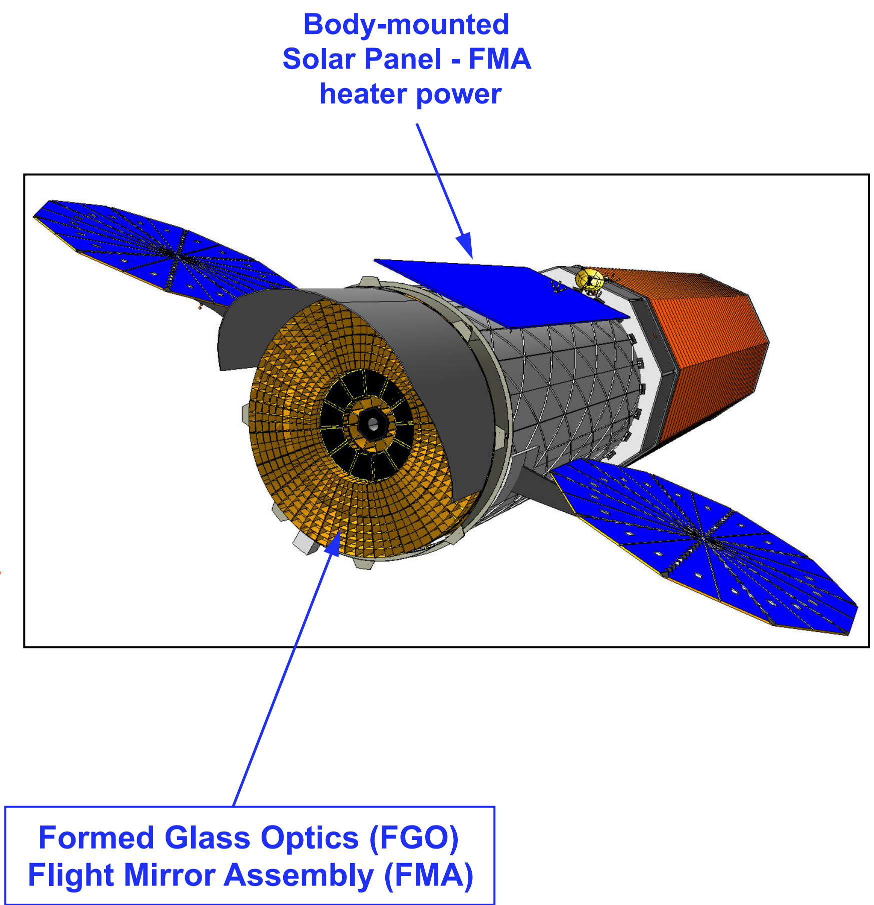
- **Science objectives:**
  - Black holes and matter under extreme conditions
  - Galaxy formation, galaxy clusters and cosmic feedback
  - Life cycles of matter and energy
- **Mission**
  - Large area achieved with single mirror with extensible metering structure to achieve 20 m focal length
  - X-ray observatory at L2 semi-major axis 800,000 km orbit
  - Launch on EELV or Ariane 5 in 2021
  - Throw mass ~ 6425 kg
  - Mission life: 5 years required, 10 years goal



Stowed configuration

IXO Observatory Configuration





Traceability of Mission Reqt's to FMA Reqt's

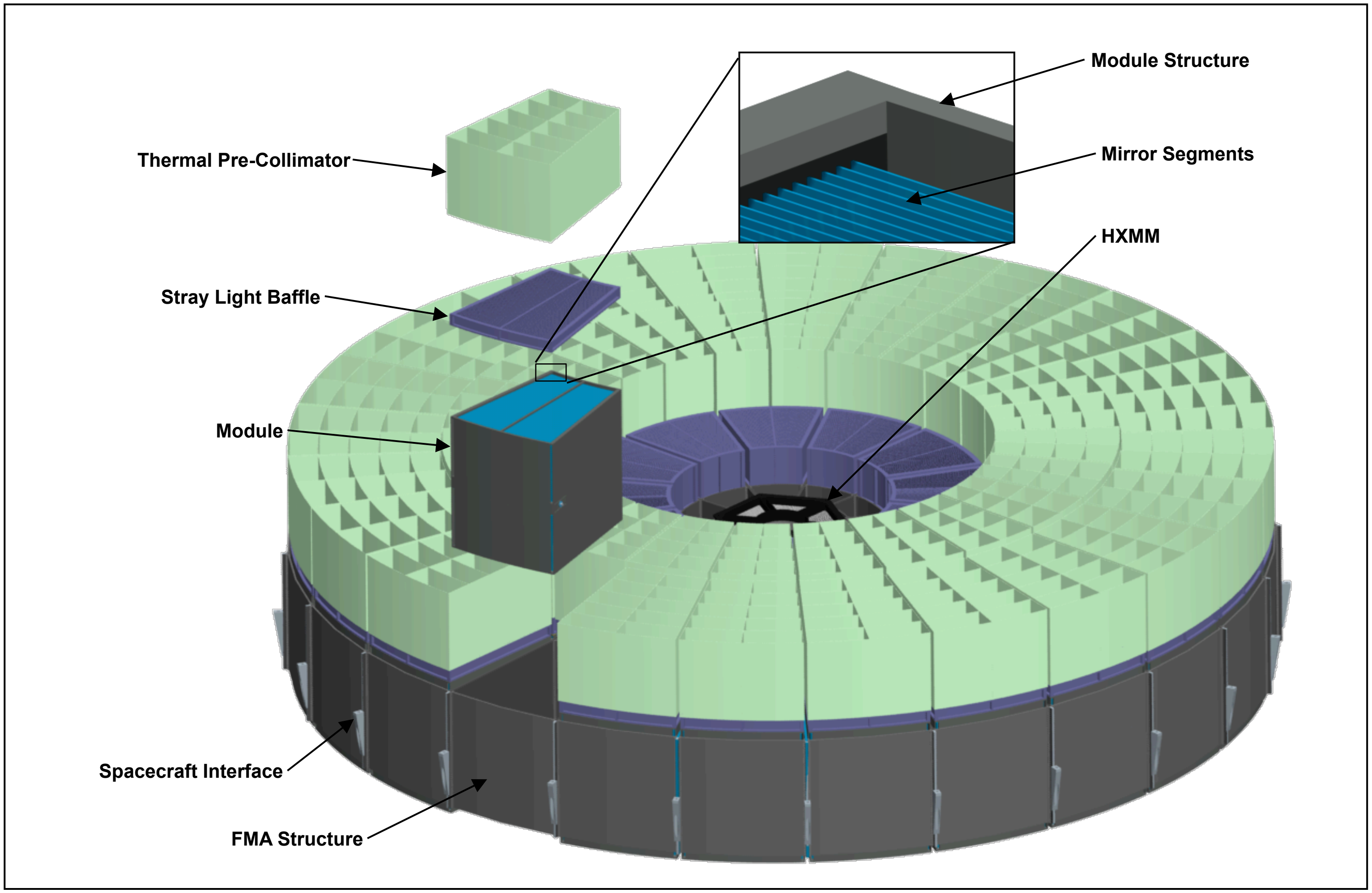
IXO Mission Performance Requirements that Drive FMA Requirements

Mirror Effective Area *	3 m^2 @1.25 keV 0.65 m^2 @ 6 keV 150 cm^2 @ 30 keV	Black hole evolution, large scale structure, cosmic feedback, Equation of State (EOS) Strong gravity, EOS Cosmic acceleration, strong gravity
Observatory Angular Resolution *	≤5 arc sec HPD <7 keV ≤30 arc sec HPD > 7 keV	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution Cosmic X-ray Background (CXRB)
Field of View	18 arcmin < 7 keV 8 arcmin > 7 keV	
Energy Bandwidth	0.1 to ≥ 40 keV	Determination of continuum for measuring spin of accreting black holes Strong gravity CXRB studies

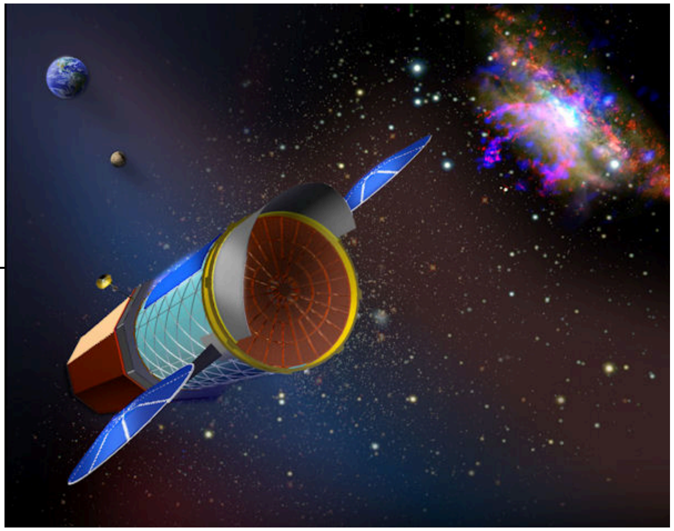
*** Reference N. White, Jan. 2009 presentation to AAS**

FMA Overview

- FMA Primary Structure
- Soft X-Ray Telescope (SXT) - 60 modules
- Hard X-Ray Mirror Module (HXMM) - 1 module



FMA-Level Requirements and System Design



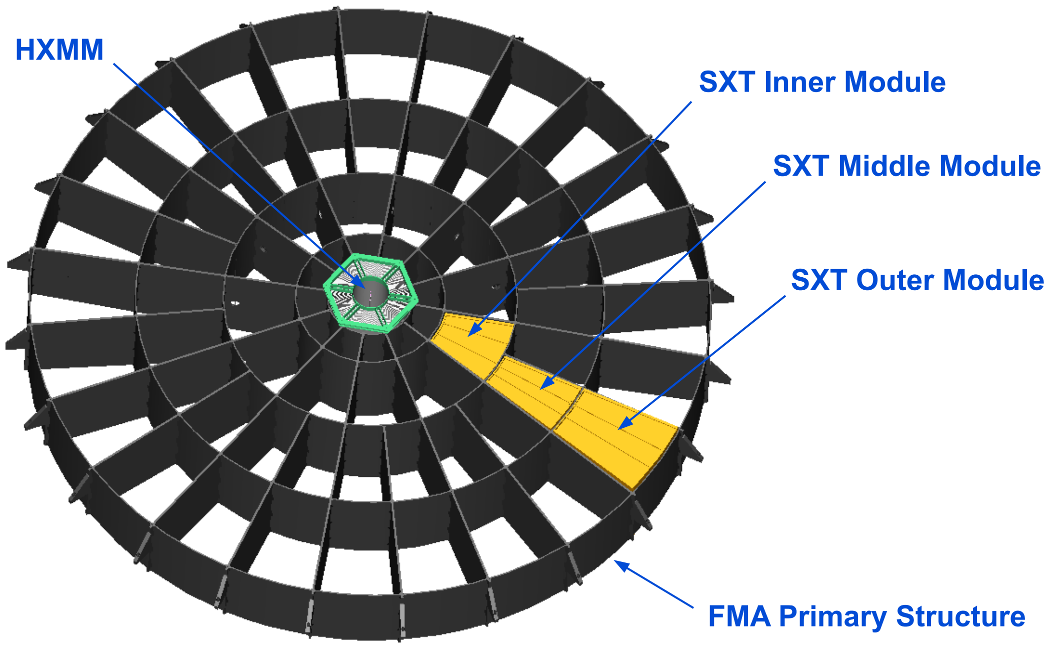
FMA Top-Level Requirements

<table>
<tr><th colspan="4">FMA Requirements</th></tr>
<tr><th>Item No.</th><th colspan="2">Description</th><th>Attribute</th></tr>
<tr><td>1</td><td colspan="2">Focal Length (m)</td><td>20</td></tr>
<tr><td>2</td><td colspan="2">Single Mirror - Outer Diameter Fits within LV Fairing (m)</td><td>3.4 for EELV</td></tr>
<tr><td>3</td><td colspan="2">Mirror Outer Diameter (Inner Surface of Last Mirror Shell) (m)</td><td>3.2</td></tr>
<tr><td>4</td><td colspan="2">Angular Resolution (arcsec) (FMA on-orbit)</td><td>4.6</td></tr>
<tr><td>5</td><td colspan="2">Angular Resolution (arcsec) (FMA as-built)</td><td>4.0</td></tr>
<tr><td>6</td><td colspan="2">System Angular Resolution below 7 keV (arcsec HPD)</td><td>≤ 5</td></tr>
<tr><td>7</td><td colspan="2">System Angular Resolution above 7 keV (arcsec HPD)</td><td>≤ 30</td></tr>
<tr><td rowspan="4">8</td><td rowspan="4">Effective Area</td><td>m^2</td><td>keV</td></tr>
<tr><td>3.0</td><td>1.25</td></tr>
<tr><td>0.65</td><td>6</td></tr>
<tr><td>0.015</td><td>30</td></tr>
<tr><td>9</td><td colspan="2">Energy Bandwidth (keV)</td><td>0.1 to 40</td></tr>
<tr><td>10</td><td colspan="2">Field of View below 7 keV (arcmin diameter)</td><td>18</td></tr>
<tr><td>11</td><td colspan="2">Field of View above 7 keV (arcmin diameter)</td><td>8</td></tr>
<tr><td>12</td><td colspan="2">FMA Mass (kg)</td><td>1731</td></tr>
<tr><td>13</td><td colspan="2">FMA Power (W)</td><td>1540</td></tr>
<tr><td>14</td><td colspan="2">FMA Operating Temperature (°C)</td><td>20 ± 1</td></tr>
<tr><td>15</td><td colspan="2">FMA Survival Temperatures (°C)</td><td>10 minimum
30 maximum</td></tr>
</table>

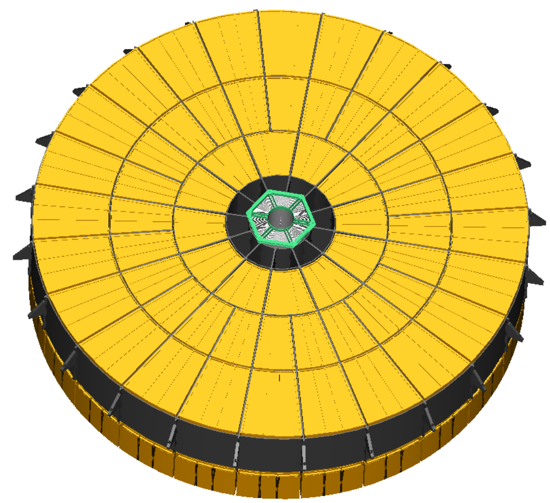
FMA SXT Optical System Attributes

- The FMA optical system design is captured with only 5 components:
  - 3 unique SXT module designs accommodate the low-energy mirror shells (361 total):
    - Identical modules are produced to fully-populate each ring (60 total modules)
  - 1 HXMM module design accommodates the high-energy mirror shells (170 total)
  - 1 Primary Structure design accommodates the 61 symmetrically arranged modules

5 Unique Designs Required for the FMA



Fully-Populated FMA

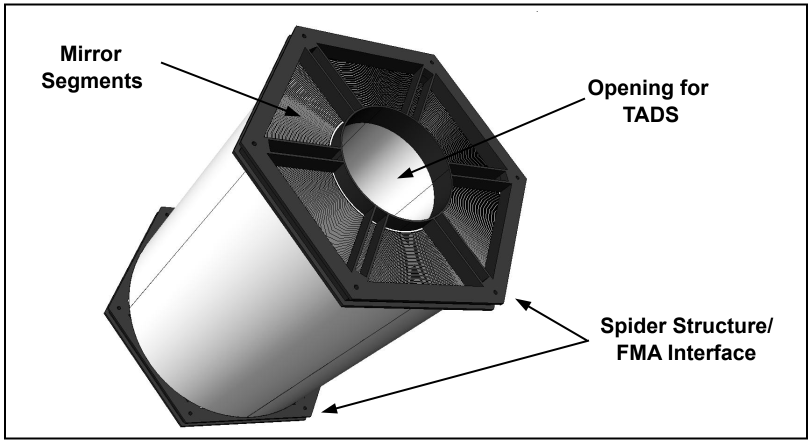


361 SXT Mirror Shells
13,896 SXT Mirror Segments
60 SXT Modules, 1 HXMM

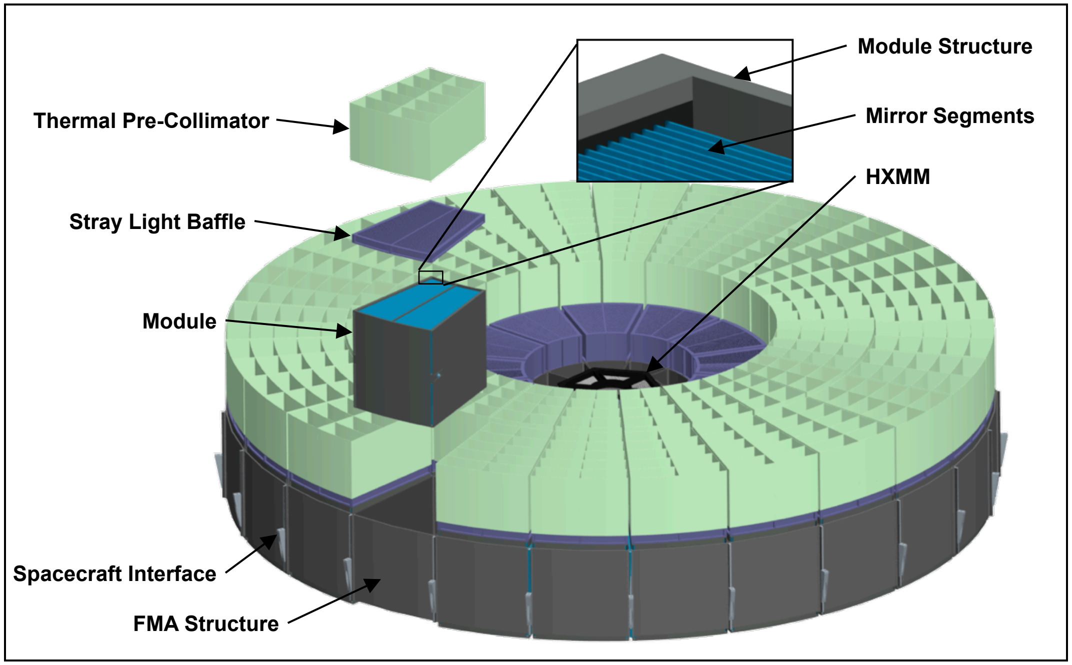
FMA Subsystems

- **Optical Subsystem:**
  - Soft X-Ray Telescope (SXT):
    - Primary and Secondary mirror segments
    - Stray Light Baffles
  - Hard X-Ray Mirror Module (HXMM)
- **Mechanical Subsystem:**
  - Module Structure
  - FMA Primary Structure
- **Thermal Subsystem:**
  - Thermal Pre-Collimators
  - Thermal Shields
  - Heaters/Harnesses

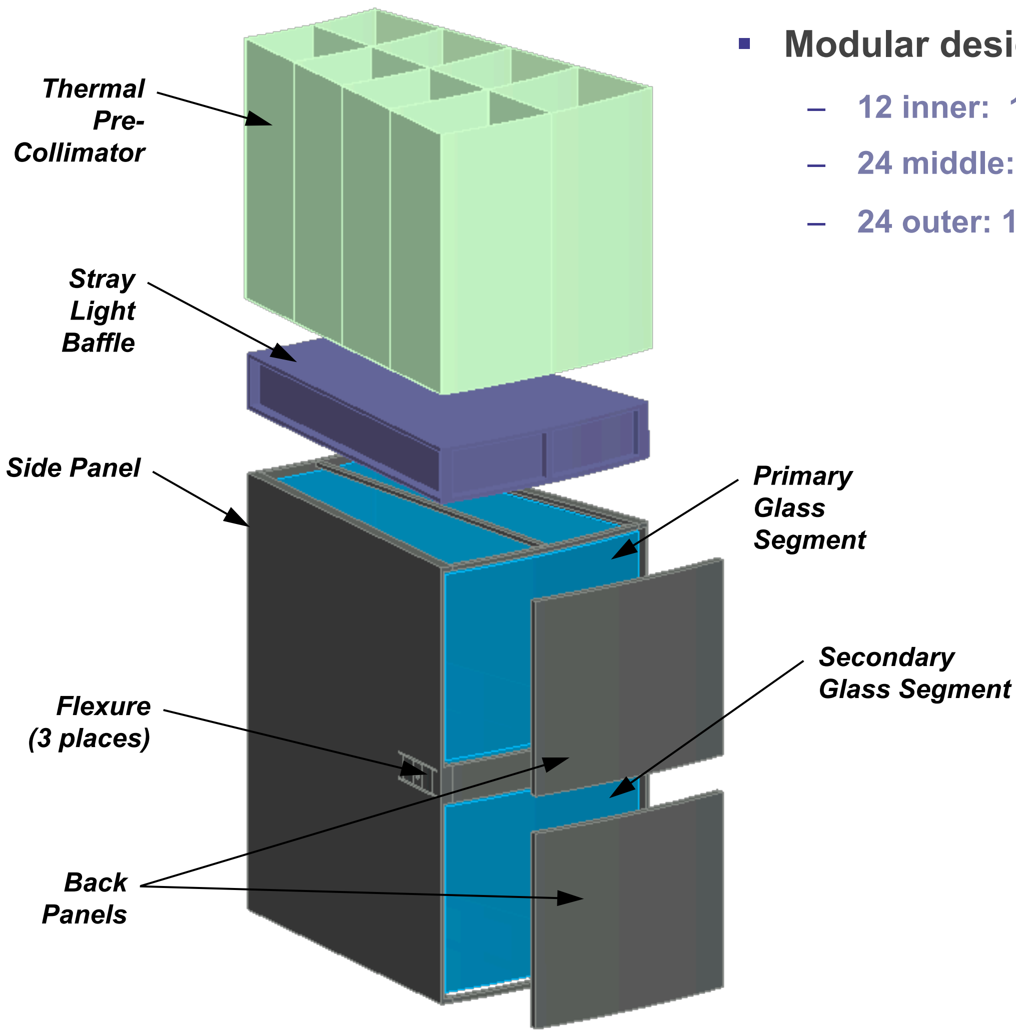
HXMM Configuration



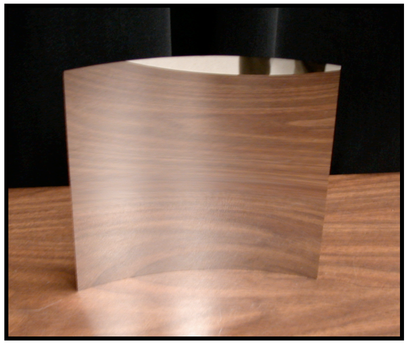
SXT Configuration



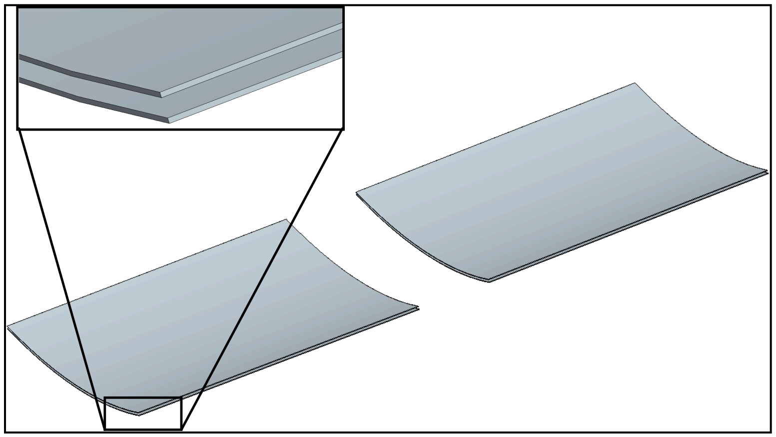
SXT Mirror Module



- Modular design: 60 modules
  - 12 inner: 143 mirror pairs each
  - 24 middle: 115 mirror pairs each
  - 24 outer: 103 mirror pairs each



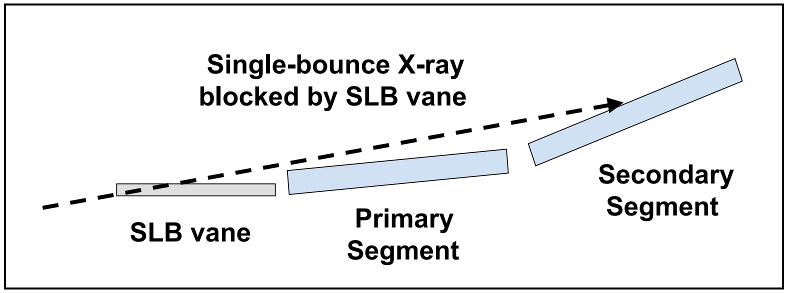
SXT Glass Mirror Segment



Scale of Nested Mirror Segment Spacing

SXT Mirror Module (cont'd)

- **Stray Light Baffle (SLB)**
  - Addresses stray light issues at the SXT focal plane
  - Additional baffles/aperture plates may be needed at the grating focal plane
  - Stray light ray trace analyses are underway



- **Thermal Pre-Collimator (TPC)**
  - Thermal control method for open-aperture telescopes
  - Minimizes heat flow while maintaining unrestricted opening for collimated X-rays
  - Mirror segments have low conductance - small heat flows can cause temperature gradient-induced optical distortions
  - Collimates both incoming X-rays and thermal radiation from the mirror to space
  - Limits the mirror segment's view to space and reduces conductive loss to space
  - Establishes a thermal gradient in the axial direction to present a lower temperature to space
  - Optical cavity @ 20 °C vs. space @ 3 K

FMA SXT Angular Resolution Budget

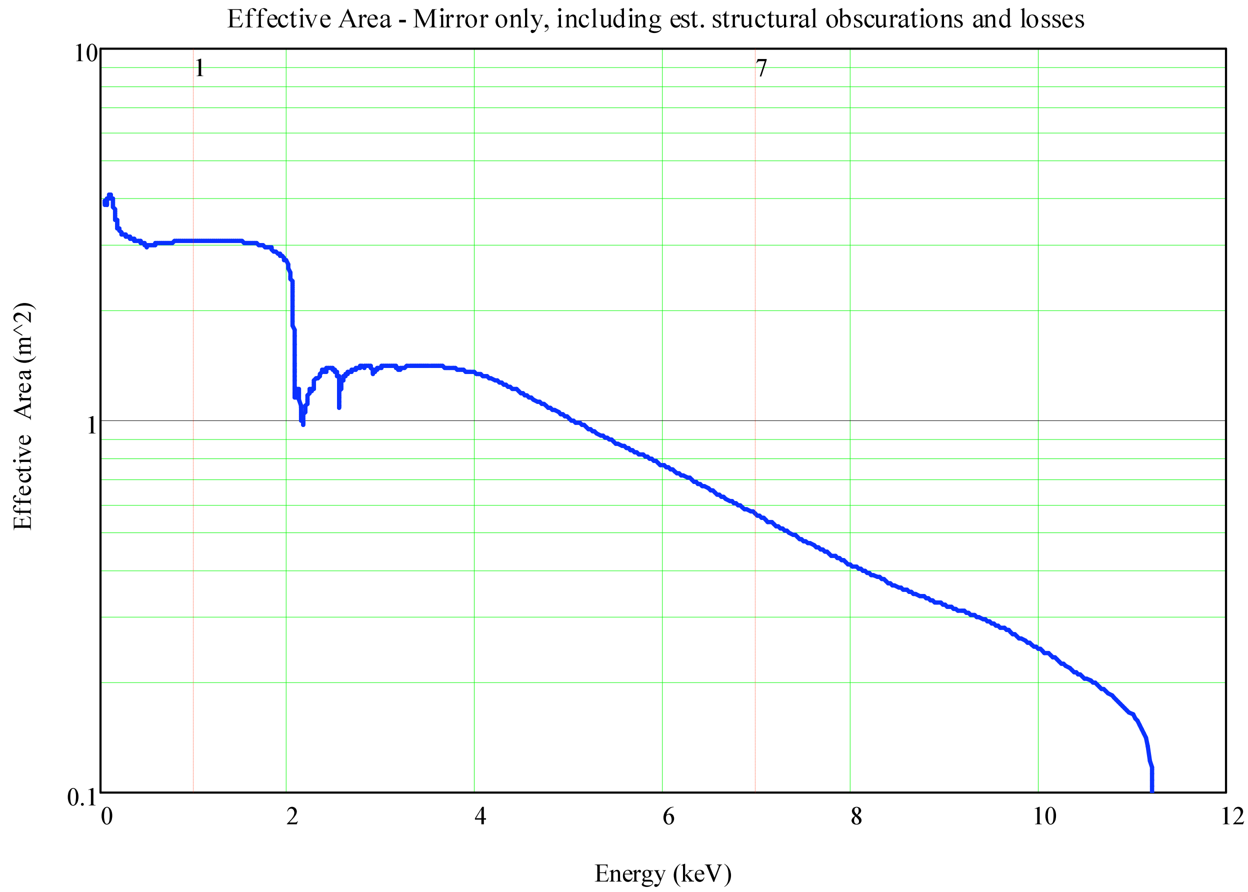
- **5.0 arcsec HPD Mission-Level:**
  - Includes detector pixelization, Observatory thermal and jitter, ground processing, attitude reconstruction, etc.
- **4.6 arcsec HPD FMA on-orbit:**
  - Includes gravity release, launch shifts, FMA thermal effects, etc.
- **4.0 arcsec HPD FMA as-Built:**
  - Module Assembly (3.6 arcsec HPD)
    - Pair of Perm. Bonded Mirror Segments (3.5 arcsec HPD)
      - Pair of Temp. Mounted Mirror Segments (3.2 arcsec HPD)
        - Individual Perm. Bonded Mirror Segment (2.6 arcsec HPD)
          - Individual Mirror Segment (2.2 arcsec HPD)
            - Forming Mandrels (1.5 arcsec HPD)

Effective Area Budgets

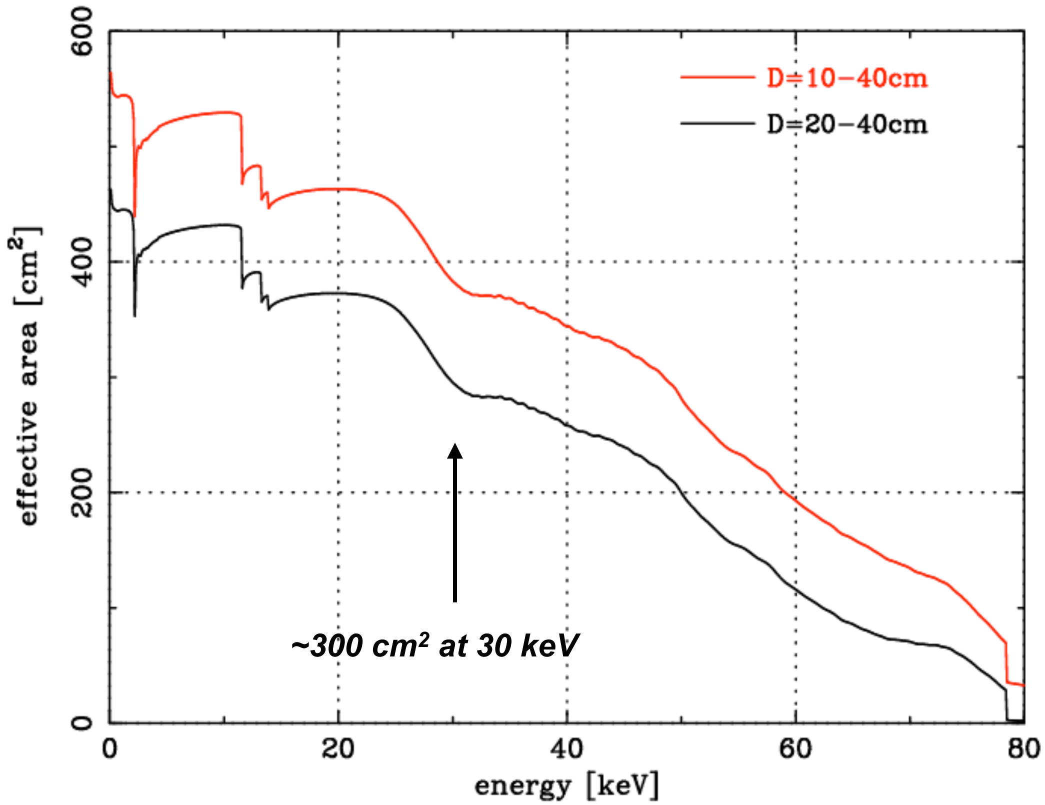
- **Mirror Effective Area at 1.25 and 6 keV:**
  - **Mirror design prescription used to calculate geometric clear aperture for each shell:**
    - **Design includes a variety of requirements, discussed later.**
  - **Reflectance calculated shell by shell as a function of area:**
    - **Use Iridium coating with 95% of bulk density**
  - **Structural obscuration included (from mechanical design of FMA structure)**
  - **Allocated loss factors applied:**
    - **2% for secondary to primary misalignment**
    - **2% for particulate contamination**
    - **Large angle scatter (= scattering outside the largest detector field-of-view) applied:**
      - » **Assume mirror meets surface roughness requirements**
- **Mirror Effective Area from 7-30 keV:**
  - **Same approach as for 1.25 and 6 keV, except:**
    - **Use multilayer coating on HXMM**
    - **HXMM 0.4 mm thick aluminum pre-filter serves two purposes:**
      - » **Works as a thermal filter**
      - » **Reduces/eliminates contribution of HXMM to SXT point spread function, in the event that HXMM point spread function is poorer than its 5 arc-sec HPD goal**

FMA Effective Area Chart

- **SXT mirror effective area after accounting for losses due to:**
  - Structural obscurations
  - Budgeted alignment (2%, energy independent)
  - Particulate contamination (2%, energy independent)
  - Scattering (energy dependent)



HXMM Effective Area Chart



- **Mirror only - more than meets the requirement of 150 cm^2 at 30 keV**
- **Does not include effect of aluminum soft X-ray pre-filter**
- **Does not include blockage due to the TADS components**

FMA Mass Budget

- The FMA mass is an allocation from the Observatory-Level
- The mass contingency is 16%

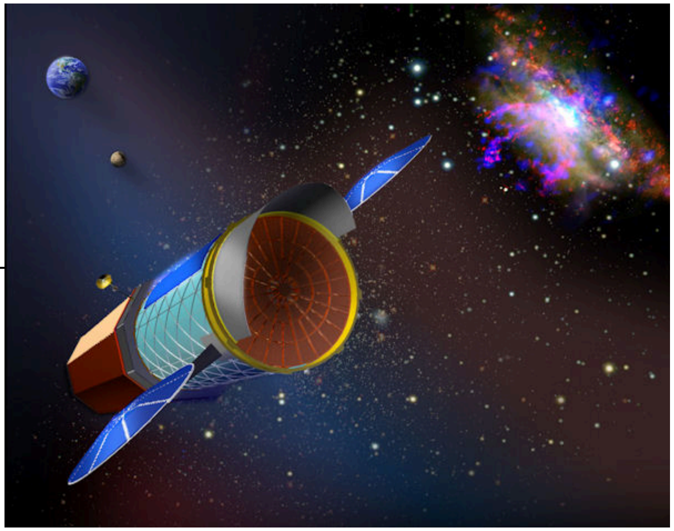
FMA Summary Mass Information (kg)		
	Current Best Estimate Mass	Maximum Expected Mass
FMA Total Mass	**1731**	**2009**
Total SXT Glass Mass	733.2	843.2
Total SXT Module Structure Mass	482.1	561.2
Total SXT Thermal Heaters/Controllers	18.0	21.6
Total SXT Thermal Harness	12.7	19.6
Total Mass Supported by FMA Structure	1391.5	1618.4
Mass of FMA Structure	339.8	390.7
Total HXMM Mass	50.8	58.6

Based on Mass Growth Allowance per AIAA S-120-2006

FMA Contamination Requirements

- Review and assess Chandra requirements, and add additional requirements, to establish a baseline for the FMA
- Flow-down from effective area (take geometric area out)
- Assign an FMA contamination expert to further define requirements
- Known contamination elements:
  - The FMA will have covers on each side
  - The FMA will be purged
  - Tents/covers will be employed during integration to protect from Foreign Object Debris (FOD) and contamination

FMA Optical Design



FMA Optical System Requirements

- All requirements are met with the current FMA design

FMA Optical Design-Related Requirements			
Item No.	**Description**		**Attribute**
1	Focal Length (m)		20
2	Single Mirror - Outer Diameter Fits within LV Fairing (m)		3.4 for EELV
3	Mirror Outer Diameter (Inner Surface of Last Mirror Shell) (m)		3.2
4	Angular Resolution (arcsec) (FMA on-orbit)		4.6
5	Angular Resolution (arcsec) (FMA as-built)		4.0
6	System Angular Resolution below 7 keV (arcsec HPD)		≤ 5
7	System Angular Resolution above 7 keV (arcsec HPD)		≤ 30
8	Effective Area	**m^2**	**keV**
		3.0	1.25
		0.65	6
		0.015	30
9	Energy Bandwidth (keV)		0.1 to 40
10	Field of View (arcmin diameter)		18

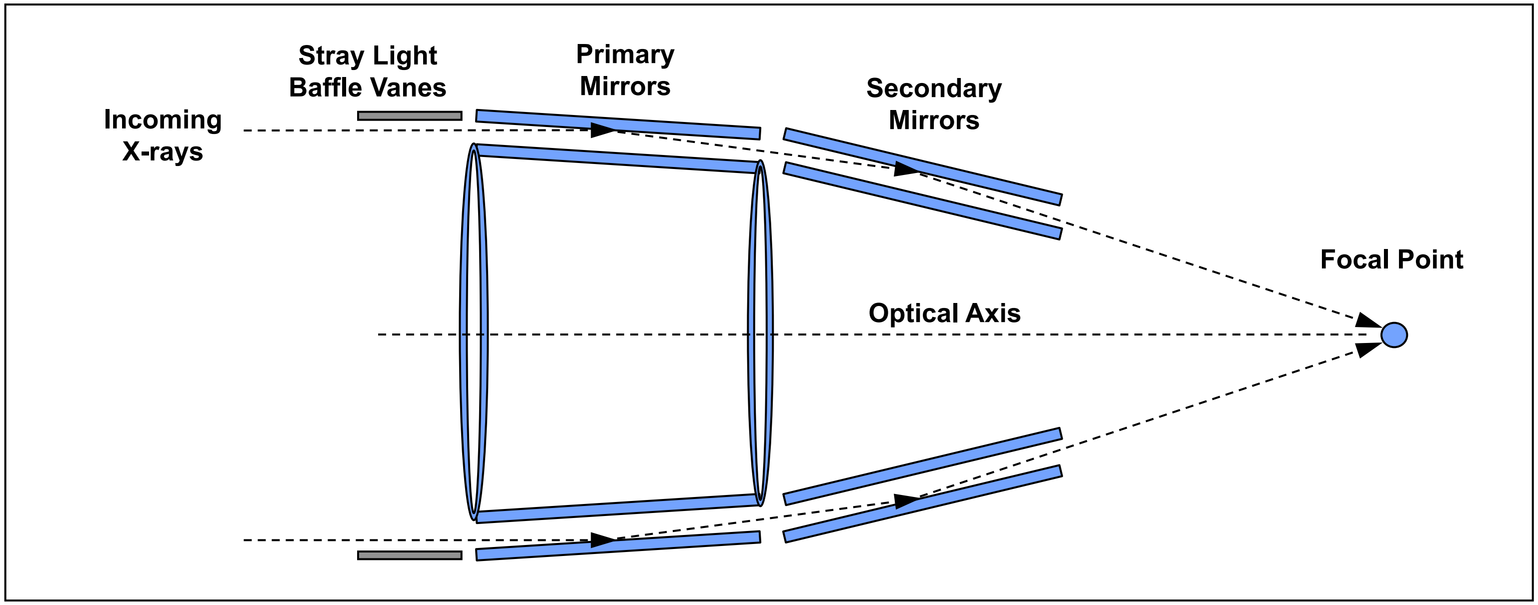
FMA Optical System Requirements (cont'd)

- All requirements are met with the current FMA design

Other SXT & HXXM Requirements		
Item No.	**SXT Requirements**	**Attribute**
1	Energy Bandwidth (keV)	0.1 to 11
2	Maximum Mirror Segment Azimuthal Size (mm)	< 400
3	Mirror Segment Axial Length (mm)	200
4	Mirror Segment Thickness (mm)	0.4
	HXMM Requirements	
1	Energy Bandwidth (keV)	8 to 40
2	Field of View (arcmin)	8
3	Mirror Inner Diameter (m)	0.2
4	Mirror Outer Diameter (m)	0.4

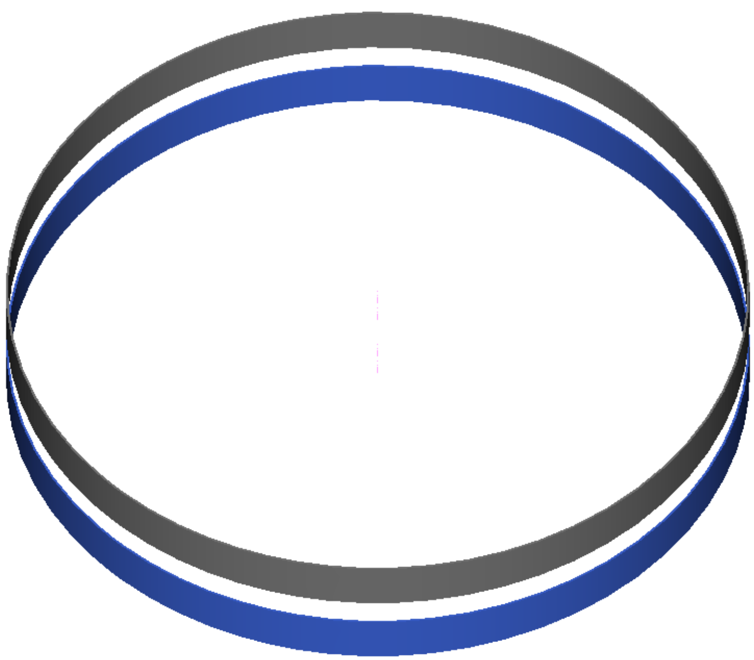
X-Ray Optics Primer

- Wolter Type I grazing incidence optics:
  - A pair of nearly-cylindrical reflectors (shells)
  - Critical angle is dependent on energy of X-ray - if angle of incidence is too high, X-ray's will be absorbed
- X-rays are focused by a primary and a secondary mirror
- Co-alignment of the two reflector elements is critical, as is maintaining a distortion-free surface figure
- Multiple mirror shells of different diameters are nested and densely packed to increase the collecting area

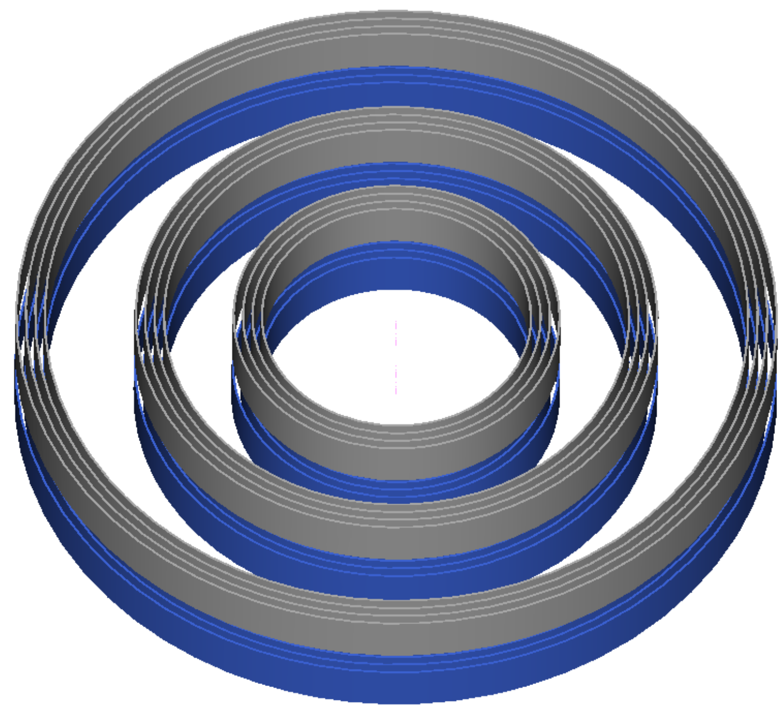


FMA SXT Optical System Design

- **Modular/segmented mirror design:**
  1. **Each mirror shell has a Primary and a Secondary mirror**
  2. **There are 361 mirror shells, grouped into 3 radial rings**



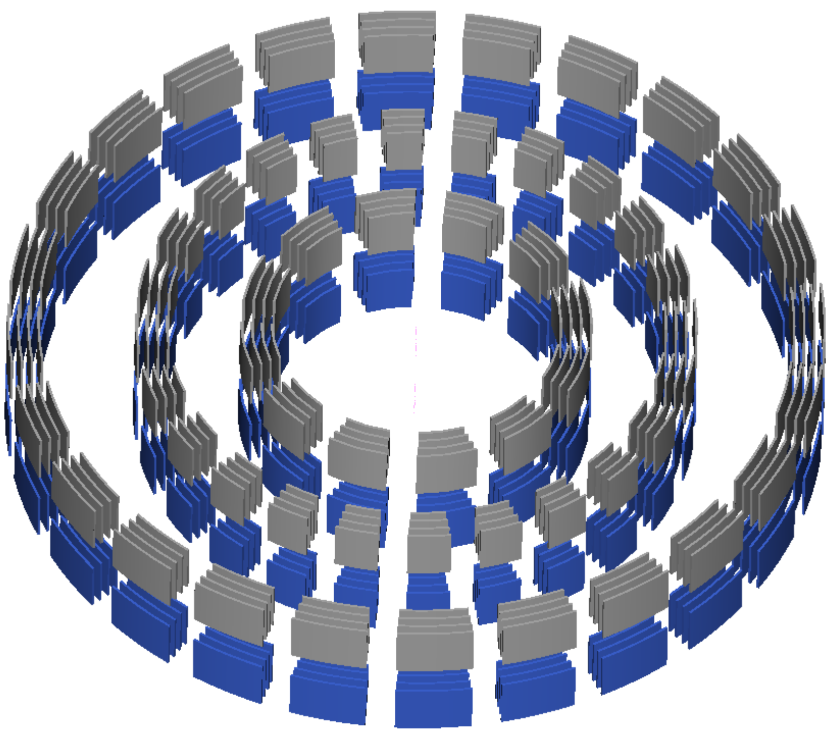
1. Mirror Shell with Primary and Secondary Mirror



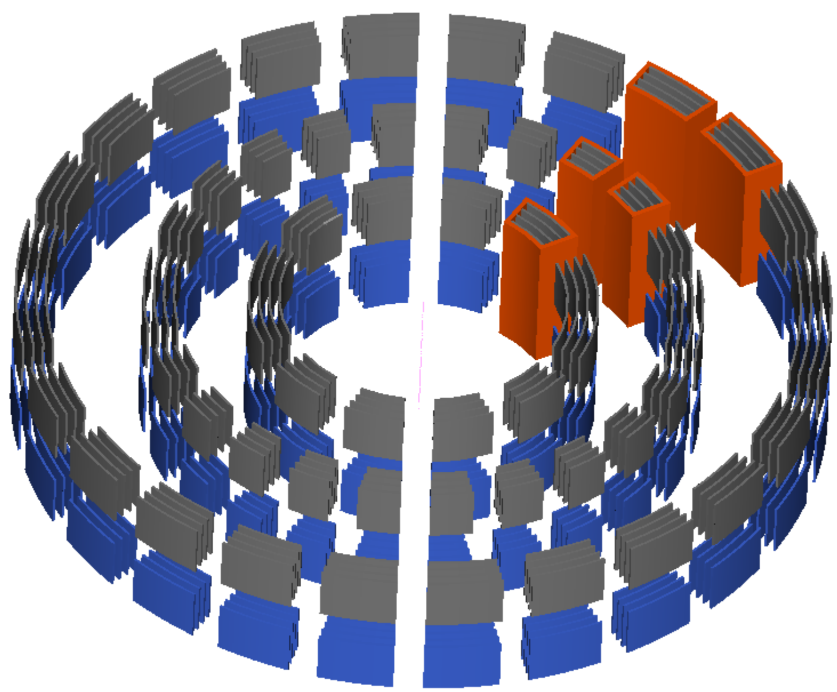
2. 361 Mirror Shells are Grouped into three Radial Rings (shell spacing is exaggerated, and not all shells shown)

FMA SXT Optical System Design (cont'd)

- **Modular/segmented mirror design: (cont'd)**
  3. **Each mirror shell is then divided into segments for modularity**
  4. **Each set of grouped mirror segments within a ring are housed in Modules**

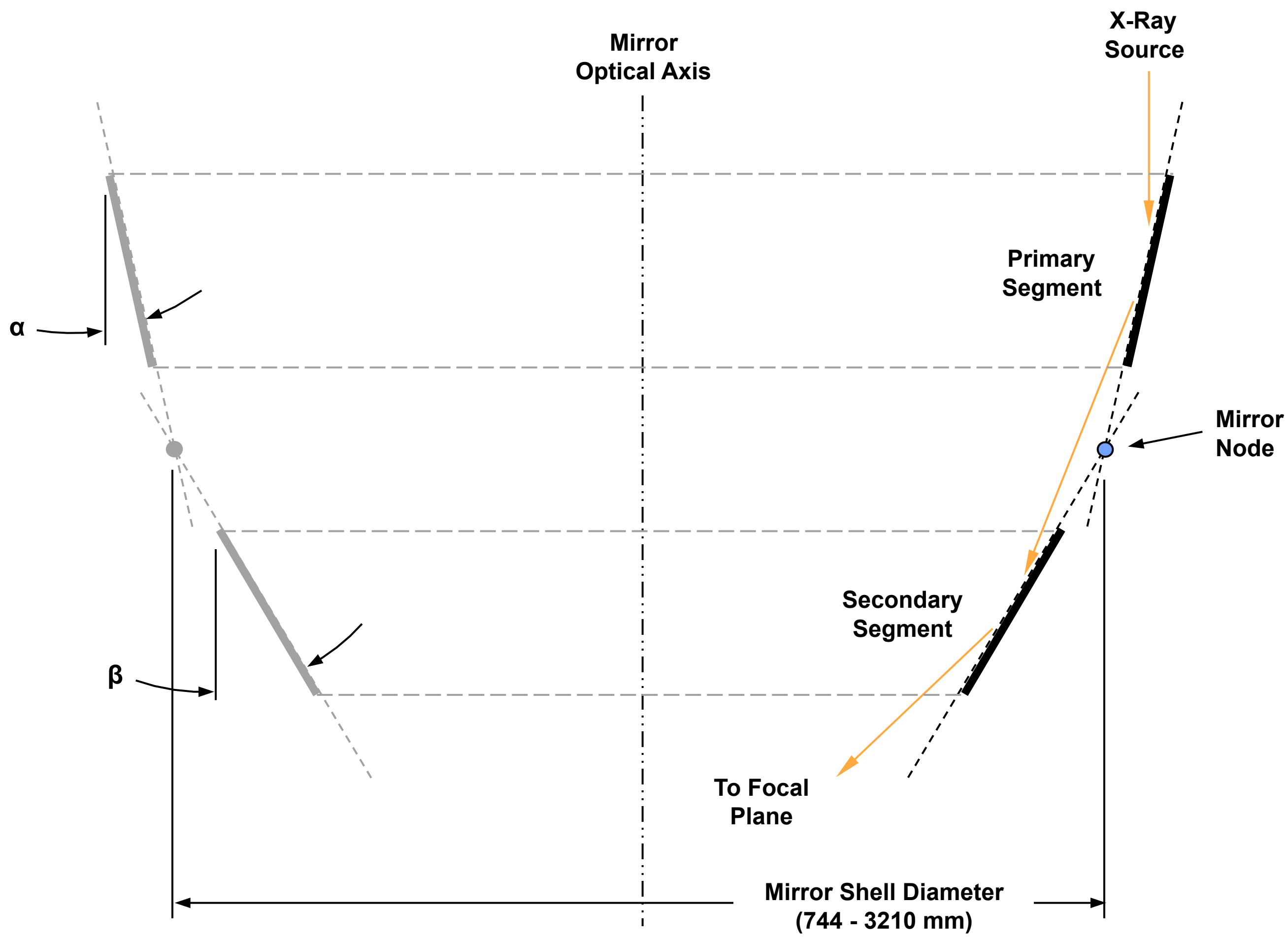


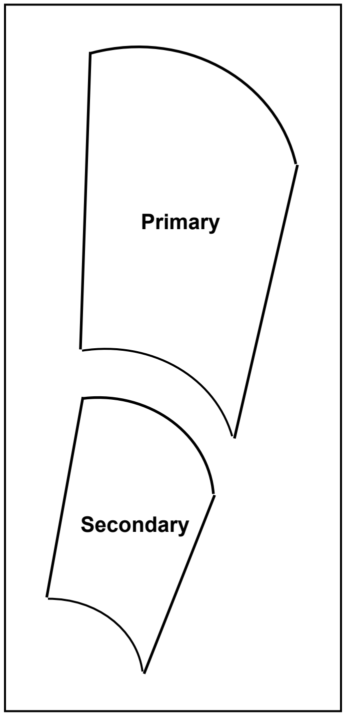
3. Mirror Shells are Divided into Segments



4. Modules then House the Groups of Segments in Each Ring (One Wedge Shown)

FMA SXT Mirror Anatomy - Attributes of a Mirror Shell



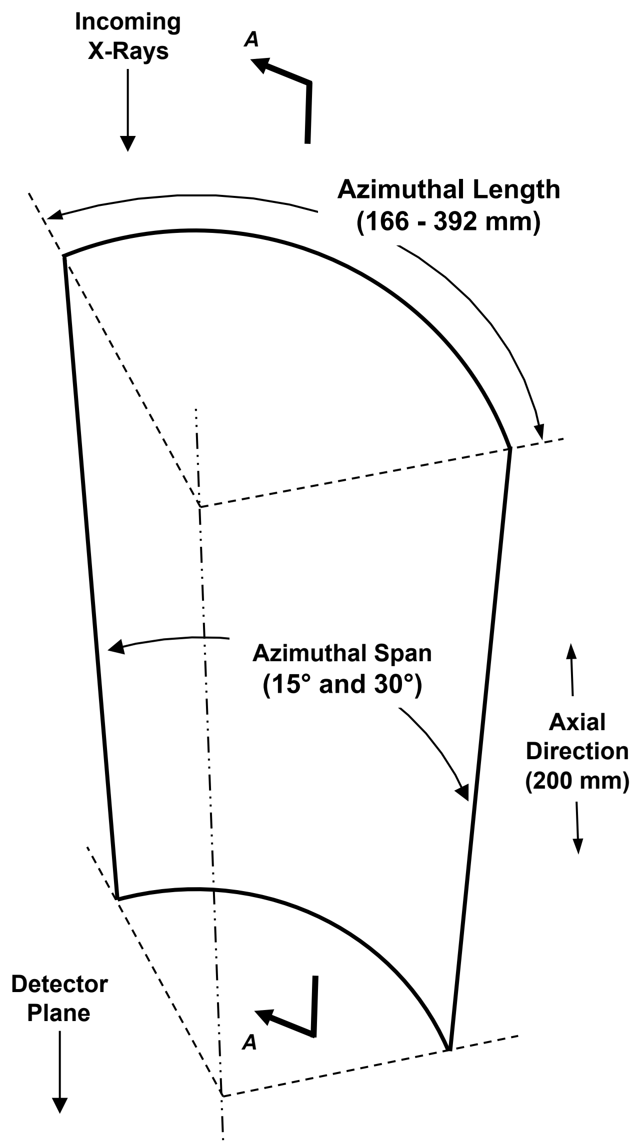


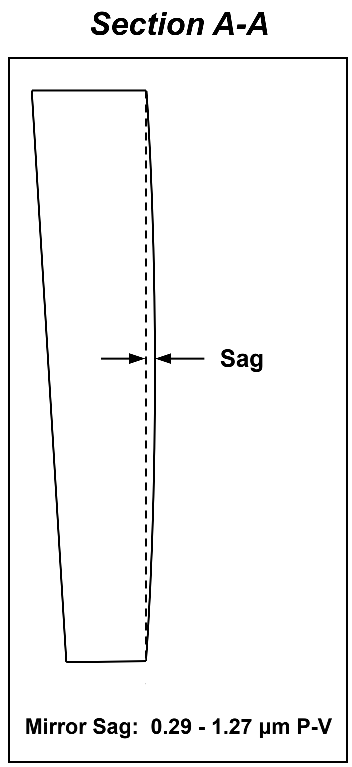
Mirror Cone Angle:

α = Primary CA - varies from ~ 0.27° - 1.15°

β = Secondary CA - varies from ~ 0.81° - 3.45°

FMA SXT Mirror Anatomy - Attributes of a Mirror Segment





FMA SXT Optical System Attributes (cont'd)

- Comparison of the IXO FMA SXT to Other X-Ray Missions:

		Other X-Ray Missions		
Mirror Attributes	IXO	Chandra	XMM	NuSTAR
Number of Mirror Asemblies	1	1	3	2
Number of Mirror Elements	13896 segments	8 elements (4 shells)	174 shells (58 per assy)	4680 segments (2340 per assy)
Manufacturing Technology	Glass Slumping	Grinding and Polishing	Nickel Electroforming	Glass Slumping
Polished Area (m^2)	52 (722 mandrels)	20	50 (58 mandrels)	18 (75 mandrels)
Total Mirror Area (m^2)	801	20	150	91
Ratio of Total Mirror Area-to-Polished Mirror Area	15	1	3	5

Details of the Mirror Technology Development for IXO can be found in the document "Mirror Technology Development Roadmap for the International X-Ray Observatory (IXO)", 05 May 2009, previously submitted for Decadal Review.

SXT Mirror Segment Derived Requirements

- **Optical figure: 2.3 arcsec HPD (one-reflection, free-standing)**
- **Coating: ~ 15 nm coating of Iridium to enhance X-ray reflectivity**
- **Dimensional: Sized to fit into modules with smooth, fracture-free edges to prevent crack propagation**
- **Other requirements:**
  - Effective area-to-mass ratio of 20 cm^2/kg
  - Mirror segment glass thickness ~ 0.4 mm or less
- **Areas of technology development:**
  - Fabrication of mirror segments that meet requirements:
    - Goal is to fabricate mirror segments that meet all figure and performance requirements as a stand-alone unit:
      - » No active adjustment of the segments will be required to align and bond
      - » Allows concern to be focused on deformations that occur due to holding and bonding the segments
  - Develop methods, techniques, and processes to precisely align and permanently bond the mirror segments into a housing (module) - must be amenable to mass production

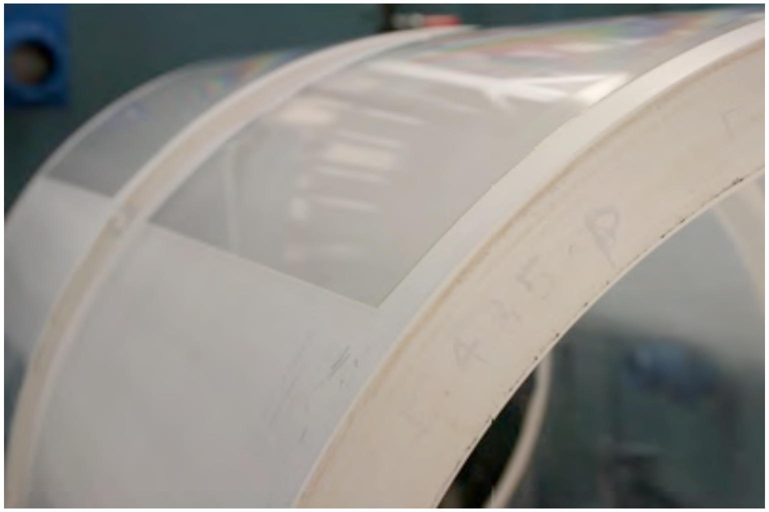
Steps of the SXT Build

- **Mirror Fabrication and Metrology:**
  - Produce mirror segments that meet requirements
- **Mirror Segment Alignment and Mount:**
  - Define processes that will allow the alignment and mounting of mirror segments in a housing within requirements
- **Mirror Modules and FMA Primary Structure Design:**
  - Design, build, and test hardware that will house mirror segments within requirements

SXT Mirror Segment Fabrication

- **Forming Mandrel - a precision-figured fused quartz element from which mirror segments are replicated in the following slumping process**
- **Slumping Process:**
  - placement of a flat glass sheet over a forming mandrel
  - placement of the mandrel into a slumping oven
  - the temperature is raised to near the glass sheet's transition temperature
  - the glass sheet deforms and sags under its own weight to conform itself to the mandrel, replicating the mandrel's figure
  - the mandrel and slumped glass sheet are slowly cooled to room temperature
  - the glass sheet is marked for cutting with a template that references the mandrel edge
  - a release layer that has been applied to the mandrel surface allows the slumped glass to be easily removed from the mandrel

Slumping of a Glass Sheet on a Forming Mandrel



Slumped Glass Sheets on Forming Mandrels

SXT Mirror Metrology Overview

- **Support mirror segments in a distortion-free state and measure them optically to characterize the mirror figure quality:**
  - **Assess the figure quality of the mirror segments**
  - **Analyze the metrology data to develop performance predictions for each mirror segment through every stage of the alignment and bonding process:**
    - **Track the cumulative distortion induced at each step**
    - **Create a performance prediction at the mirror segment level**

SXT Mirror Segment Align & Mount Overview

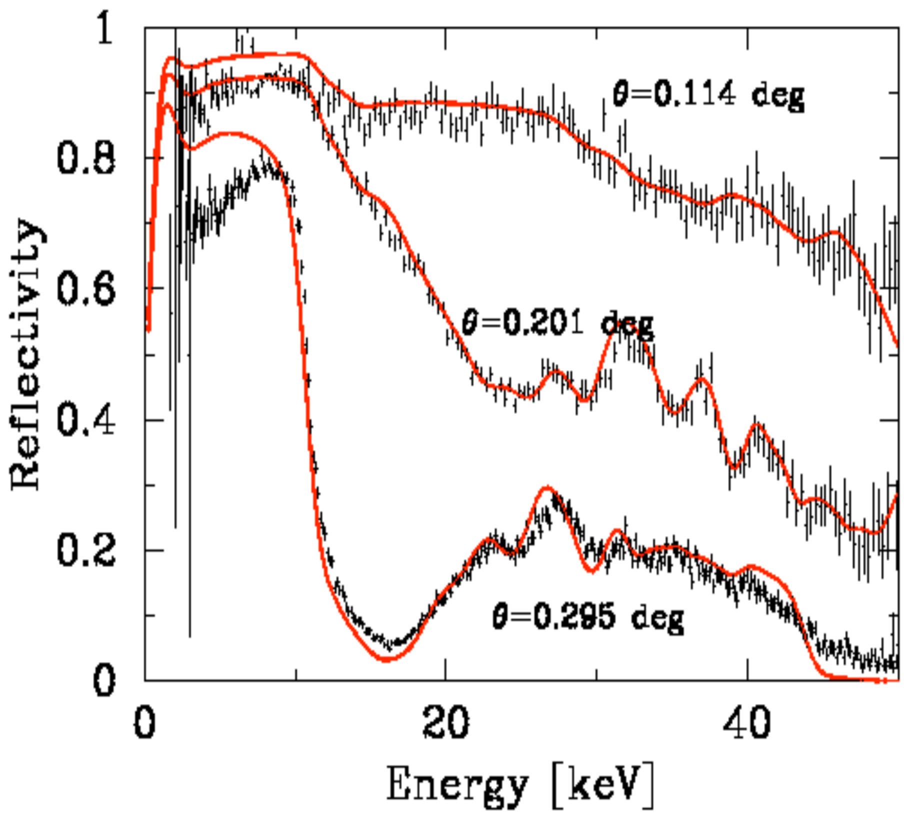
- **The alignment and mounting process requirements are:**
  - Maintain the optical figure of the mirror segment
  - Provide sufficient support and stability such that the mirror segment can withstand launch loads without degradation of its optical or mechanical performance
  - Simultaneously accommodate requirements for accuracy, speed, cost
- **Process steps:**
  - Mount each mirror segment for transfer to the permanent housing
  - Align the mirror segment to the housing
  - Permanently bond the mirror segment to the housing

HXMM Optical System Design

- Conical approximation to Wolter I (intrinsic blur is < 3 arcsec HPD)
- Segmented mirrors rather than full shells (just like SXT)
- Baseline optical design has 40 cm outer diameter, 20 cm inner diameter
- Each segment is 20 cm in axial length
- Segments spaced radially to optimize on-axis effective area (maximum packing density)
- Mirror segments are 0.2 mm D263 glass
- Total number of shells is 170
- Assume NuSTAR mounting approach - 6 azimuthal segments per full shell
- Total number of segments is 2,040
- Reflecting surfaces are graded Pt/C multi-layers (prescription on next page)
- Radiation below 10 keV is attenuated by a 0.4 mm aluminum filter (that doubles as a thermal shield)

Graded Multilayer Prescription for HXMM

- Pt/C multi-layers
- Same prescription used for all micropore and glass mirrors



θ(deg)	N	d_{max}(Å)	d_{min}(Å)
0.110	28	126.4	46.2
0.123	37	117.8	40.0
0.135	56	117.8	35.3
0.152	79	117.8	31.6
0.169	93	117.8	28.6
0.187	121	106.5	26.1
0.208	138	98.5	24.0
0.230	138	98.5	24.0
0.253	123	88.5	24.0
0.280	123	88.5	24.0
0.310	108	77.4	24.0
0.342	108	24.0	24.0

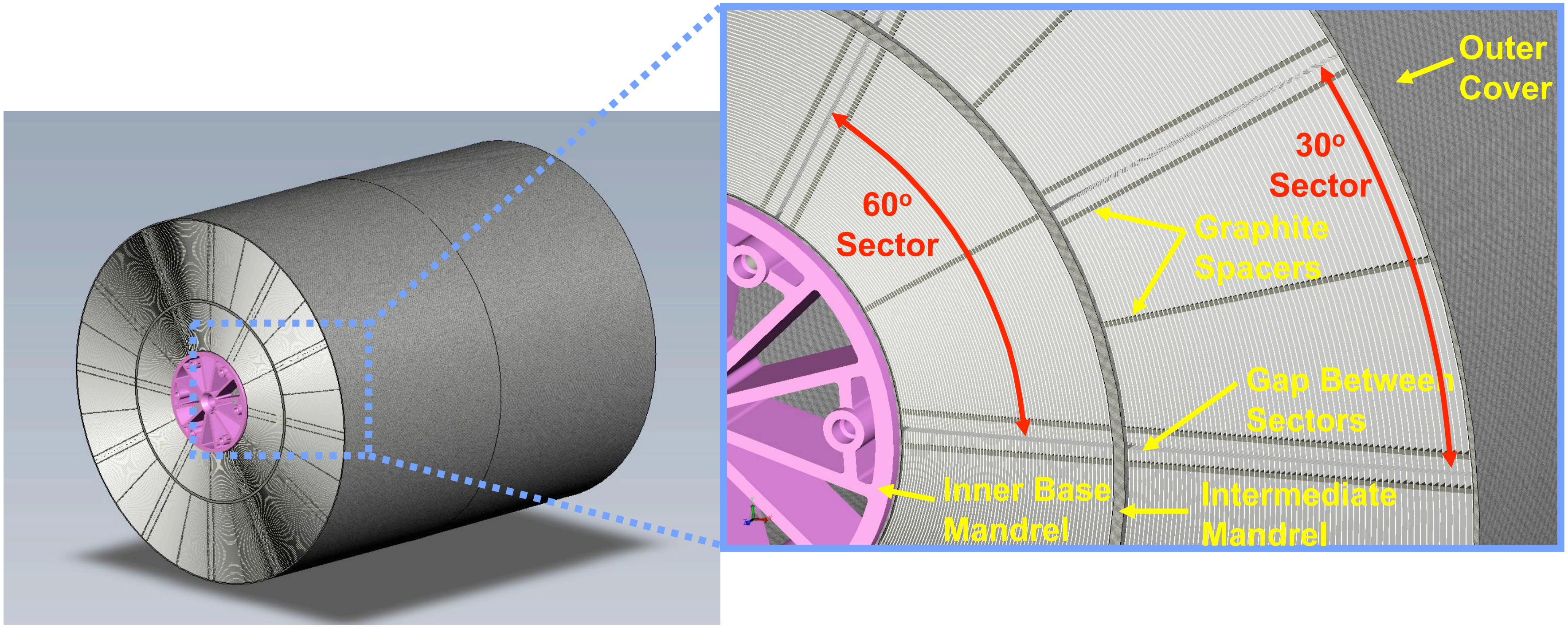
$\theta \leqq 0.3$ degrees ← $d \geq 25$Å

HXMM Glass Mirror

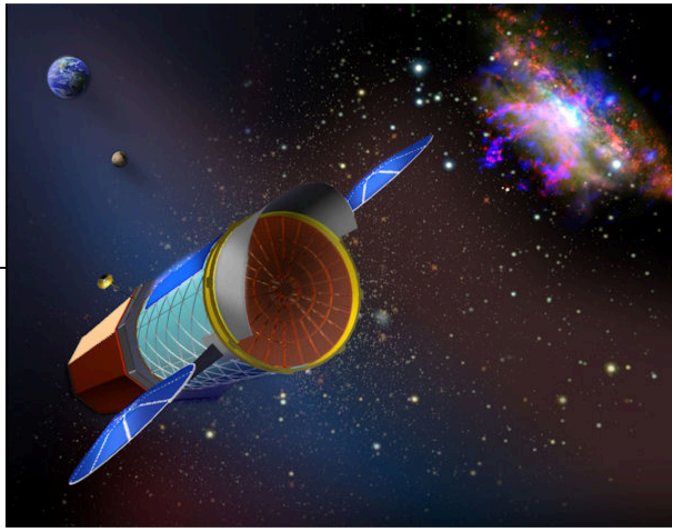
- Similar to FMA approach but with more extensive heritage
- Approach is currently being implemented in NuSTAR SMEX
- Glass segment mass production has been demonstrated
- Mounting scheme was used on High Energy Focusing Telescope (HEFT) balloon mirror
- HEFT mirror has been tested environmentally tested successfully:
  - Vibration and acoustic for Delta II

HXMM Mechanical Design Is Based on NuSTAR

- Mechanical structure includes inner & outer cylinders, front & rear spiders
  - Titanium or composite
- Intermediate mandrel is unnecessary
- Total mass of assembly is 51 kg

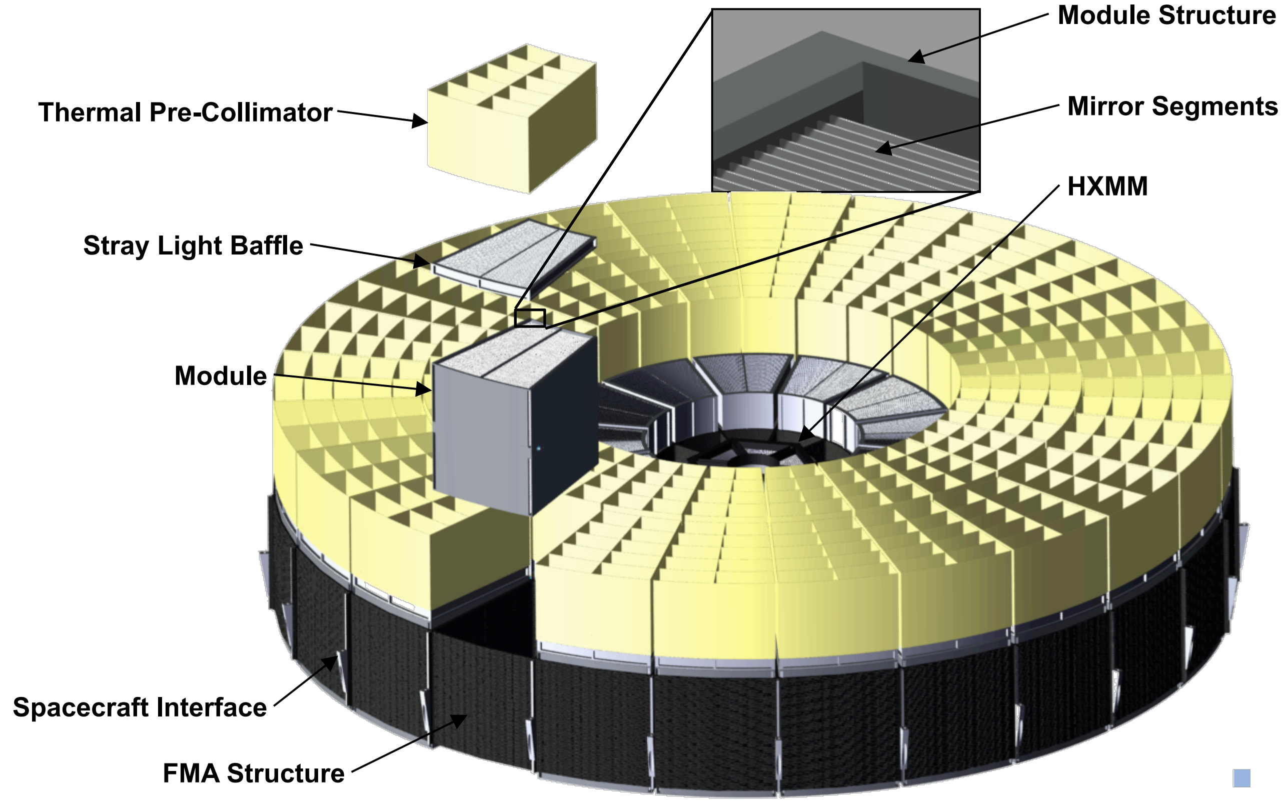


FMA Structure Design and Analysis



FMA Overview

- Carrier structure supporting 60 SXT modules containing 206-286 bonded-in mirror segments per module:
  - Overall dimensions: 3.4 m structural outer diameter x 0.8 m axial depth
  - No new technology required for structures:
    - Technology development is focused on assembling mirror segments into a module
- Single Hard X-ray Mirror Module (HXMM) located at center of structure:
  - Same interfaces as SXT module



Structural Requirements

- Effective area of 3.0 m^2 at 1.25 keV and 0.65 m^2 at 6.0 keV:
  - Drives need for thin closely packed mirror segments and minimal structural projected area
- Mission angular resolution of 5 arc-sec:
  - Drives need to limit thermal distortion through material selection and thermal design
- FMA mass no greater than 1731 kg:
  - Drives need to optimize structure for mass
- Minimum first mode of 15 Hz in torsion and 35 Hz axial/lateral:
  - Drives structural design and optimization
- Quasi-static design loads of 7.5 g lateral and 10.5 g axial simultaneous:
  - Drives structural design and optimization
- Support HXMM with 40 cm outer diameter (OD) in center of the primary structure

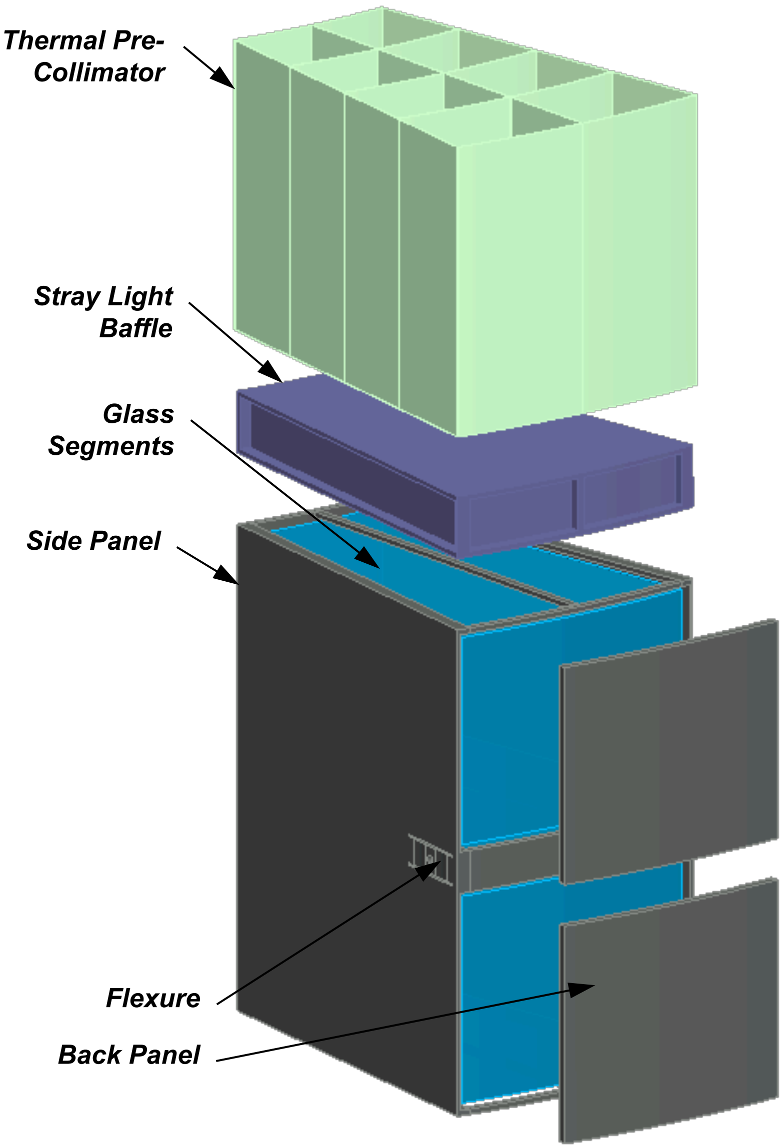
FMA Mechanical Requirements			
Item No.	Description		
1	Angular Resolution - FMA on-orbit (arcsec)		4.6
2	Effective Area	m^2	keV
		3.0	1.25
		0.65	6
		0.015	30
3	FMA structure interface diameter - 24 bolts (m)		3.4
4	FMA envelope height FWD from S/C adapter plane (cm)		60
5	Optical System segment accomodation requirements		Various
6	HXMM mirror outer diameter (cm)		40
7	HXMM mirror inner diameter (cm)		20
8	FMA Mass (kg)		1731

Structural Requirements (cont'd)

- **The FMA design leverages existing aerospace technology and does not require technology development beyond fabricating, aligning and mounting mirror segments:**
  - Standard aerospace materials and practices with extensive fight heritage used
  - Materials: Aluminum, Titanium, M55J/954-3 composite
  - Fabrication: CNC machining, composite lay-up, bolted interfaces, bonded interfaces
  - Analysis: NASTRAN structural FEA, SINDA thermal FEA, integrated optomechanical analysis
- **Assumptions:**
  - Optical design per the 3.2 m outer diameter, 20 m focal length prescription:
    - Segments made from Schott D263 glass
  - Modules are built up using a derivative of current alignment and integration method:
    - Segments bonded at discrete areas per technology development plan
  - Modular approach needed with kinematic mounting between structure and modules:
    - Monolithic FMA is undesirable - makes I&T difficult and put segments in the primary load path
  - HXMM is a deliverable to the FMA:
    - Not a part of the FMA/SXT development effort
    - Same kinematic interfaces to primary structure as SXT modules

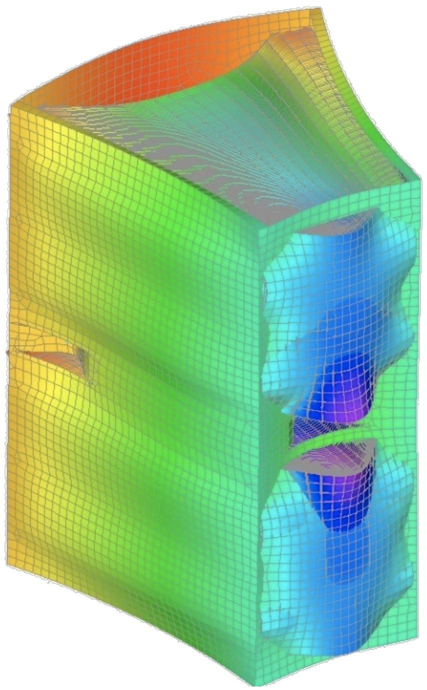
SXT Module Design

- **Module structure consists of front, back, and side structural panels:**
  - Bonding rails are fastened to inside of panels
  - Panels provide lightweight structural stiffness needed to keep the segments aligned during integration, testing, and launch
  - Panels protect the mirror segments from Foreign Object Damage (FOD)
  - Panels can be thermally controlled to reduce thermal distortion of the segments
  - Panels are as thin as possible to maximize effective area
- **Modules kinematically mount to FMA structure via three integral blade flexures**
- **Module structure made from a titanium alloy with a CTE closely matching D263 mirror segments (CTE 6.3 ppm/°C)**

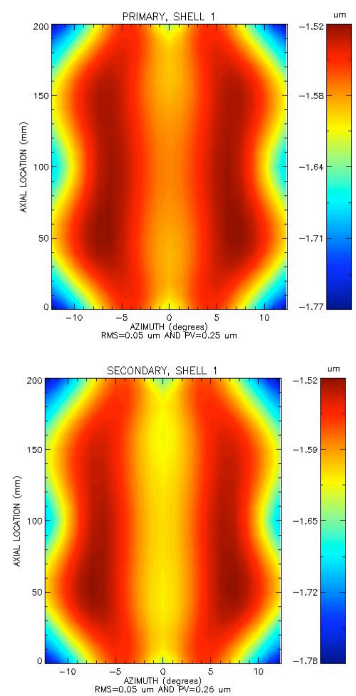


Optomechanical Analysis

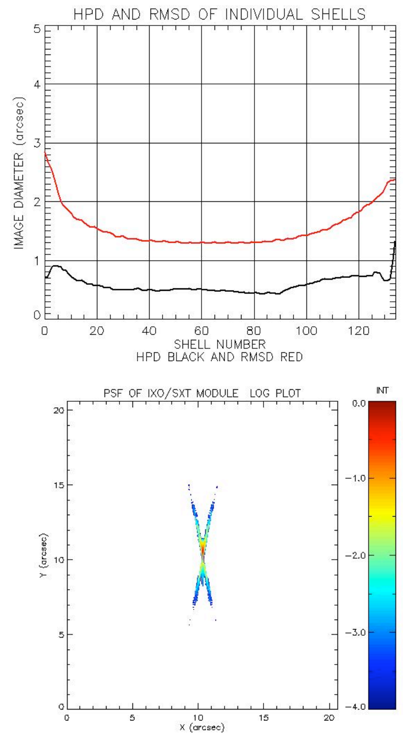
- **Performance sensitivity to thermal loads determined through optomechanical analysis:**
  - **FEMs of all 206-286 segments in module generated from optical prescription using custom software**
  - **Thermal and gravity distortion cases run using NASTRAN**
  - **Performance prediction generated based on deformed model is using custom ray tracing software**



Distorted FEM



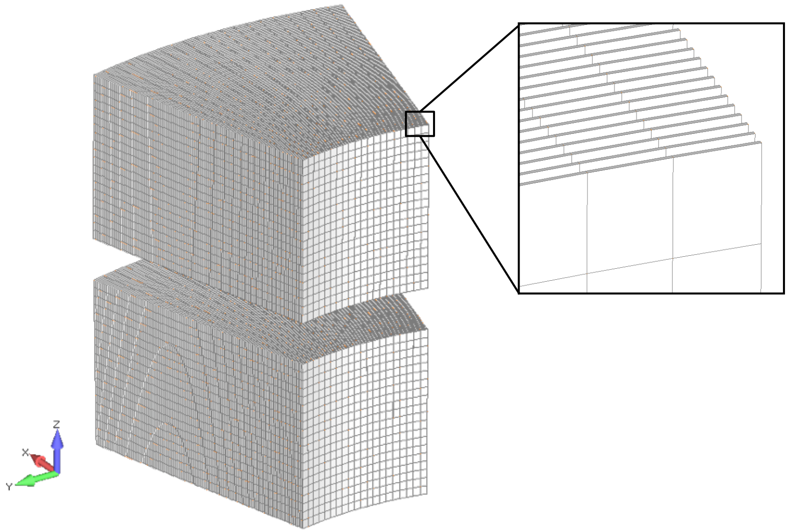
Mirror figure distortion



Performance prediction

Finite Element Modeling (FEM)

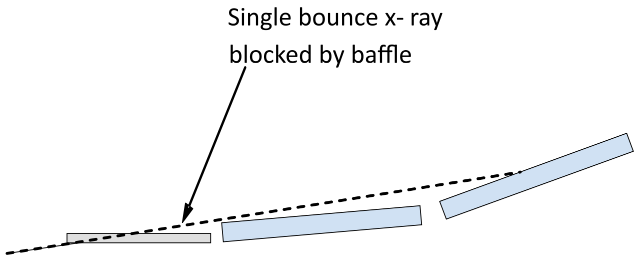
- **Investigated effect of:**
  - CTE mismatch
  - Linear thermal gradients
  - Flexure design
  - Thermal gradient between structure and segments
  - Gravity loads
- **Performance most sensitive to:**
  - Radial thermal gradient
  - Thermal gradient between segments and module structure
  - CTE mismatch between segments and module structure
- **Results used in structural and thermal design of module**
- **Full mapping of predicted temperatures from thermal model in process**
- **FEM Model details:**
  - Primary Structure model has 17,249 nodes and 16,746 elements
  - Module model has 125,738 nodes and 117,106 elements (includes mirror segments)



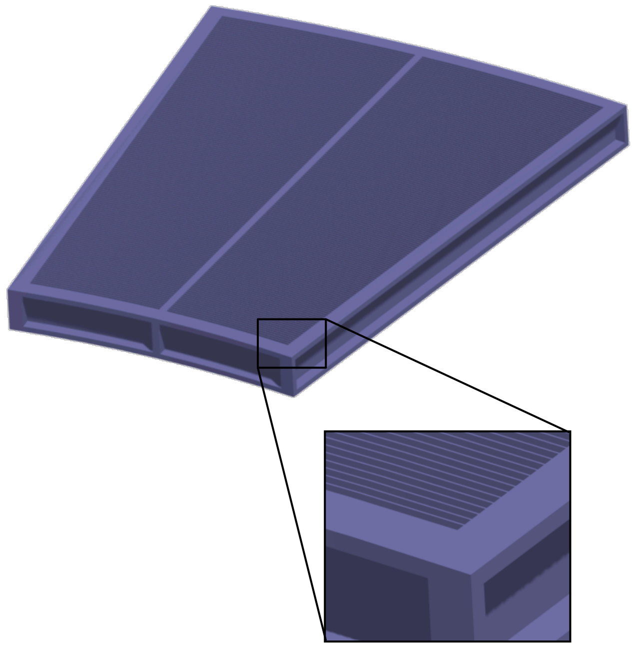
FEM of mirror segments in inner module

Stray Light Baffles (SLB's)

- **Prevent single bounce X-rays from distorting the image:**
  - **Height of baffle varies with grazing angle of segment**
  - **Aligned to mirror segments such that effective area is not reduced**
- **IXO SLB concept based on Suzaku design:**
  - **0.12 mm thick curved aluminum foils mounted in comb structure**
- **Highly conductive aluminum SLB's are heated to help replace heat lost by mirror segments to space**



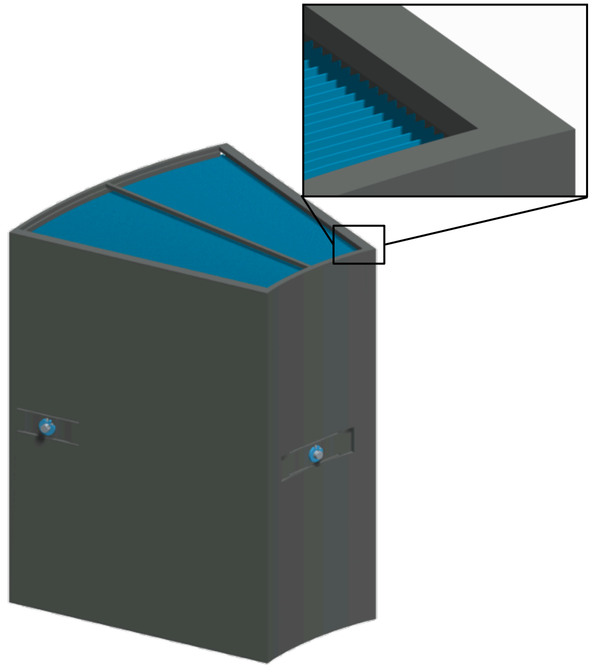
SLB functional schematic



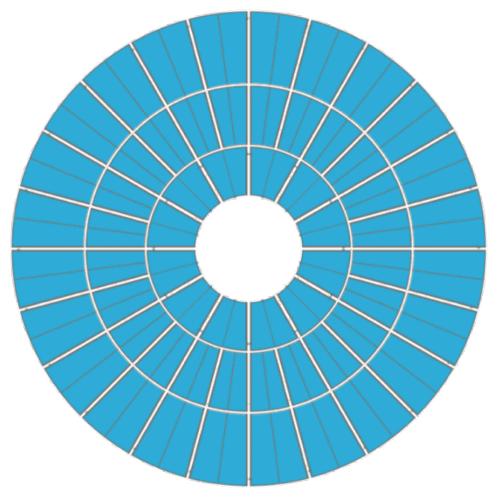
SLB CAD model with vanes for each segment

Advantages of Modular Approach

- Reduces risk:
  - If one segment or set of segments is damaged before launch, the module can be replaced
- Modules are designed to be a manageable size for assembly, transportation, and test
- Reduces FMA fabrication time:
  - Since integrating large numbers of segments will be time consuming, the modular approach allows for parallel assembly
- Reduces load in mirror segments:
  - Kinematically mounted modules take segments out of primary load path
- Reduces thermal distortion of mirror segments:
  - Kinematically mounted modules decouple the deformation of the primary structure from the deformation of the segments
- Approach is applicable to X-ray mirrors of arbitrary size:
  - If the FMA size changes in future observatory design iterations, technology developed to create a module is still directly applicable



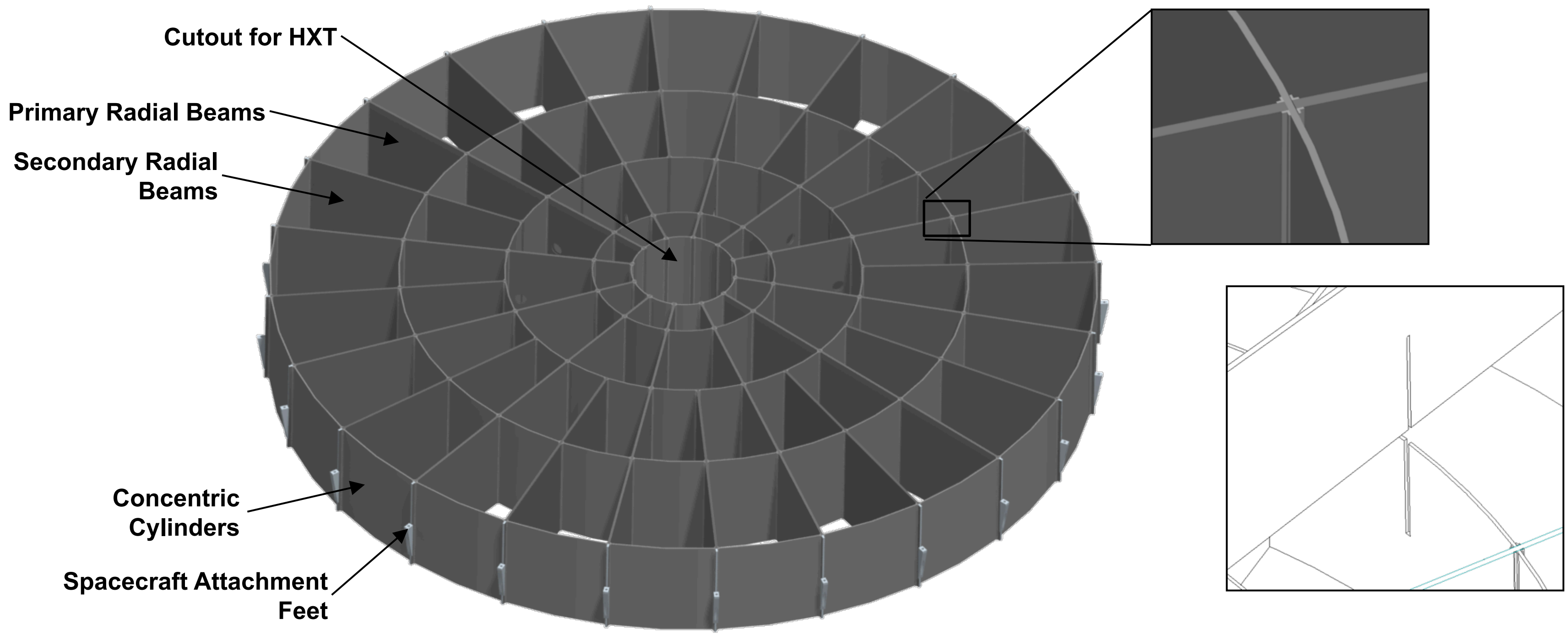
Inner module CAD model



Module layout

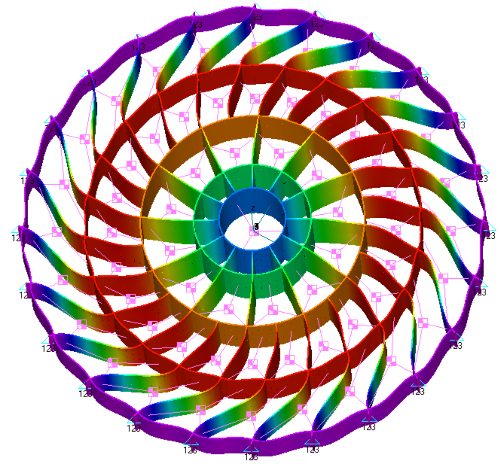
FMA Primary Structure

- Carrier structure supporting 60 kinematically mounted modules totaling ~1300 kg
- Constructed using standard aerospace materials and design practices
- All structural members made from M55J/954-3 Carbon Fiber Reinforced Plastic (CFRP) for high stiffness, low weight, and near-zero CTE
- Primary and secondary radial beams of rectangular cross sections:
  - Minimizes beam thickness and maximizes effective area
- Radial beams connected by concentric cylinders
- Bonded 'wine-box' construction with doublers in corners

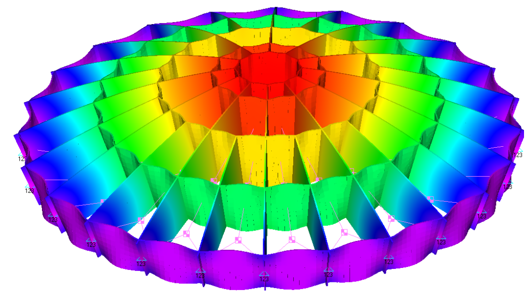


FMA Primary Structure Analysis

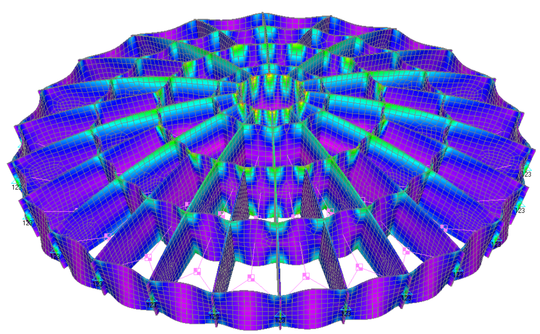
- **FEM description:**
  - Members modeled with plate elements assuming isotropic CFRP lay-up
  - Modules modeled as lump masses with kinematic mounts:
    - Assumes modules do not add stiffness to structure (conservative)
  - 3 DOF constraints at bolted interface to spacecraft
  - Member thicknesses optimized using NASTRAN SOL200
- **Design performance:**
  - Structural mass 28% of payload (module) mass
  - 17 Hz first torsional mode
  - 60 Hz first axial mode
  - 1 G axial load maximum displacement 0.1 mm
  - 10 G axial load maximum stress 30 MPa (4.4 ksi)
  - 10 G lateral load maximum stress 47 MPa (6.8 ksi)
  - Maximum interface force 15,700 N (3500 lb) due to 10 G lateral load
  - 1°C bulk temperature change distortion 0.002 mm
- **Significant room for optimization remains**



First torsional mode



First axial mode



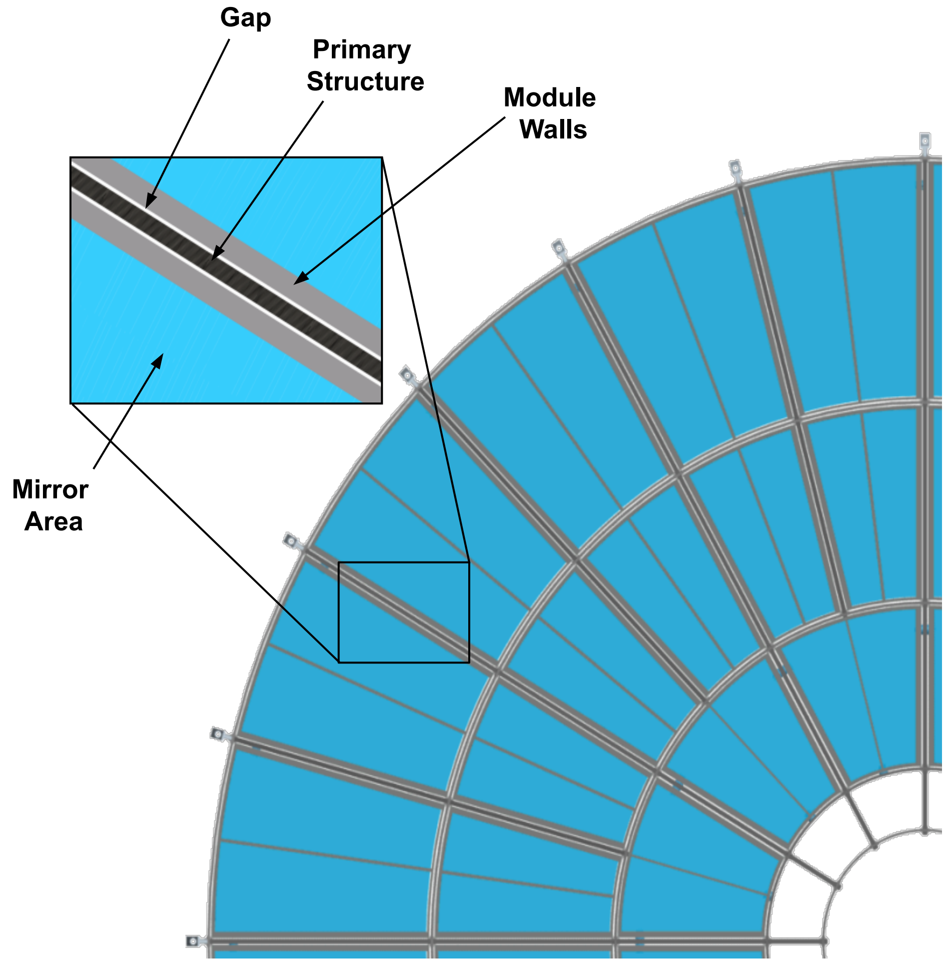
Stress due to 10G axial load

SXT Effective Area Performance

- FMA structural design optimized to maximize SXT effective area
- 46 mm of azimuthal structural per module
- 46 mm radial gap between module rings
- 15% loss due to structure at 1.25 keV
- 18% loss due to structure at 6.0 keV

Azimuthal Structure

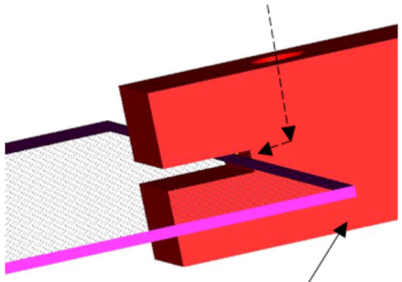
Source	Amount (mm)
Primary structure	10
Module structure	5 x 2 = 10
Gap between primary structure and module structure	2 x 2 = 4
Gap between module structure and mirror edge	2 x 2 = 4
Bonding points	3 x 6 = 18
Total	**46**



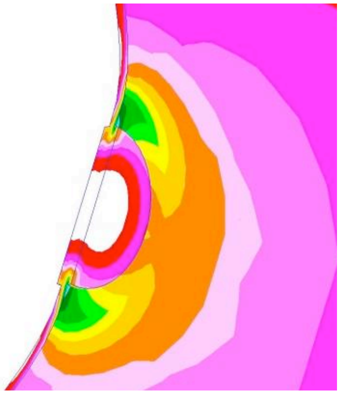
Top view of FMA Primary Structure populated with Modules - showing structural obscuration

Mirror Segment Structural Analysis

- Materials testing, FEM analysis, and mounted mirror segment environmental testing indicate FMA can be successfully launched
- Material testing:
  - Statistical glass strength determined by test of 30 samples bonded into structure to simulate module bonded condition
- Detailed FEA performed:
  - Quasi-static design loads for module determined by sine response analysis of stowed observatory model
  - Maximum stress in segments determined using detailed FEM of worst case segment
  - Positive margins demonstrated using the required 3.0 Factor of Safety
- Environmental testing of mirror segments bonded in permanent housing completed:
  - Acoustic test of three segments in a housing representing a module up to Atlas 551 qualification levels (2 minutes at 143.3 dB)
  - Successfully completed random vibration and acoustic tests of single mirror in a housing:
    - Mirror optical figure did not change throughout testing
    - Good correlation between test results and analysis



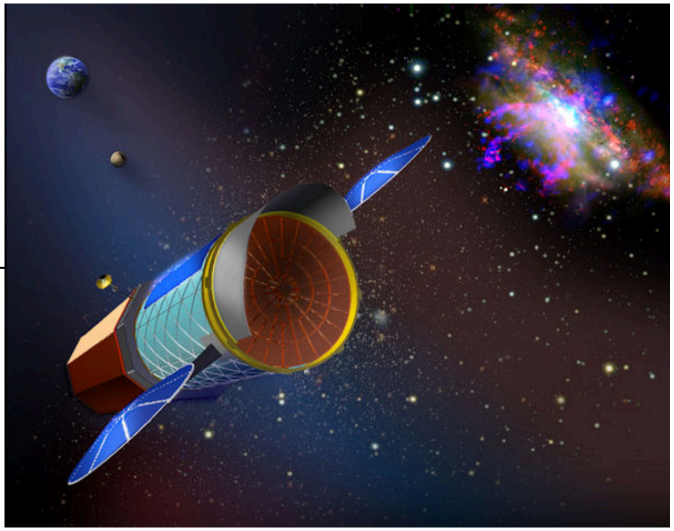
Glass test fixture



Stress near a bond point

3 Mirror acoustic test article

FMA Thermal Design and Analysis



FMA Power Budget

- The FMA power is an allocation from the Observatory-Level
- FMA power is supplied by an independent body-mounted solar panel (not coupled to the S/C power)
- Additional 30% power contingency carried at the Observatory-Level

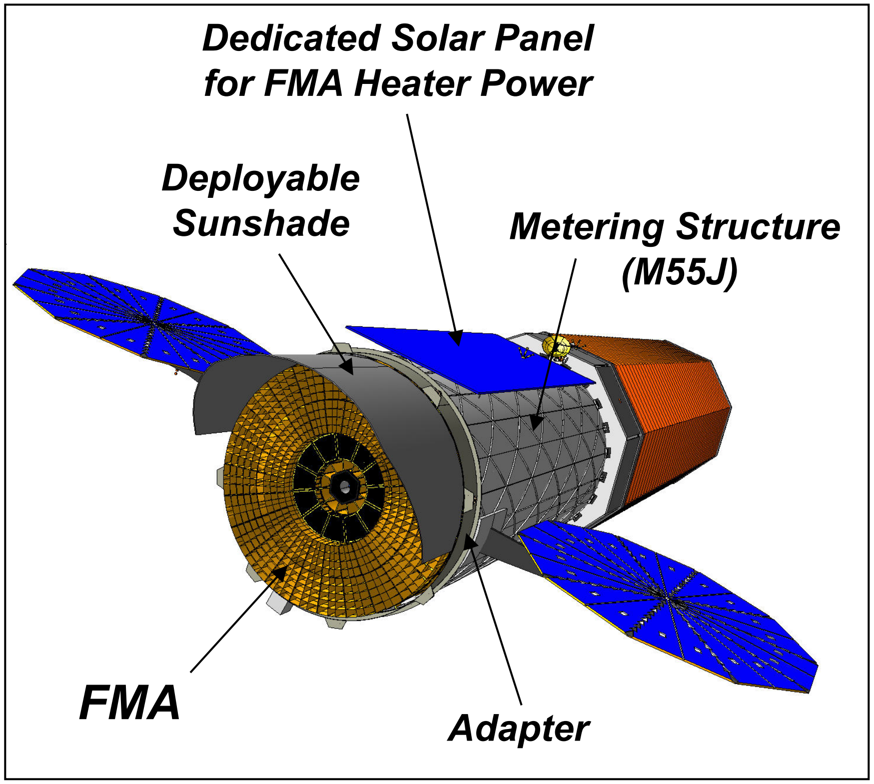
FMA Power Requirements		
Item No.	**Description**	**BOL**
1	**Total FMA/SXT heaters (W)** SXT Mirror Modules: S/C Module Metering Structure: HXMM:	**1540** 1110 420 10

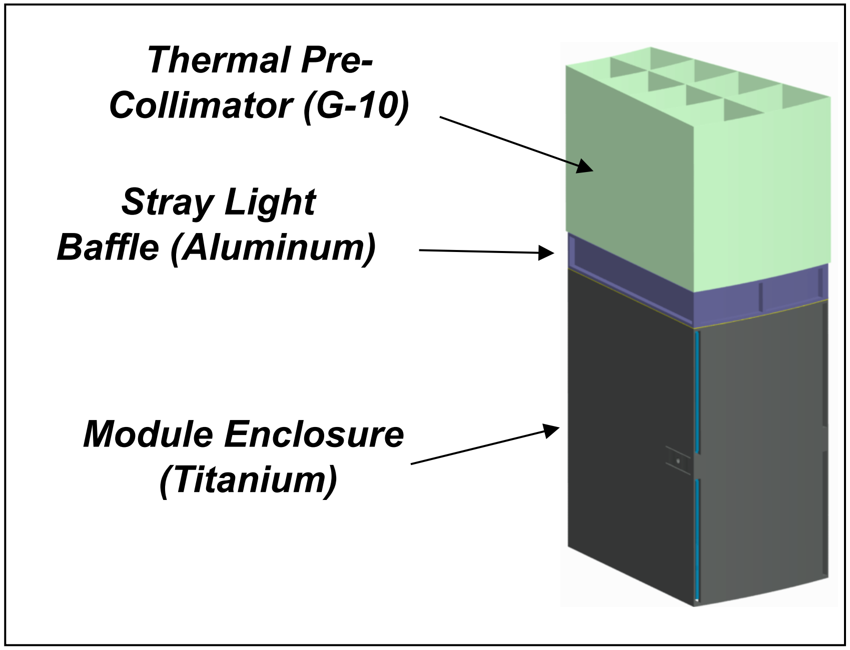
FMA Thermal System Requirements

FMA Thermal-Related Requirements		
Item No.	**Description**	
1	FMA operating temperature (°C)	20 ± 1
2	Module gradient - axially, azimuthally (ΔT)	< 1.0
3	FMA Survival Temperatures (°C)	10 minimum 30 maximum

- **The SXT operating temperature (20° C) is driven by the temperature at which the mirror segments are bonded - to avoid distorting the mirror figure you need to minimize temperature change and minimize CTE mismatch (materials choice)**
- **The SXT thermal requirements are derived from the 1.0 arcsec HPD gradient thermal distortion requirement (may need to be modified as the thermal distortion effects are modeled and verified via Structural/Thermal/Optical Performance (STOP) analysis)**

Key Thermal Components





IXO Thermal Environment

- **L2 orbit:**
  - Sun is always on one side of observatory:
    - Sun angle (angle between optical axis and solar vector) is nominally 90º
  - Earthshine and moonshine thermally negligible
  - Stable thermal environment:
    - Thermal disturbances are from sun side:
      - ± 20° yaw (70° to 110° sun angle)
      - ± 5° roll
      - Seasonal variation of solar intensity
      - Gradual degradation of thermo-optical properties due to ultraviolet exposure, charged particle bombardment and contamination
- **Thermal environment for SXT mirror segments:**
  - View to space through opening on forward end of metering structure
  - View to metering structure interior at aft end
  - View to adapter and sunshade

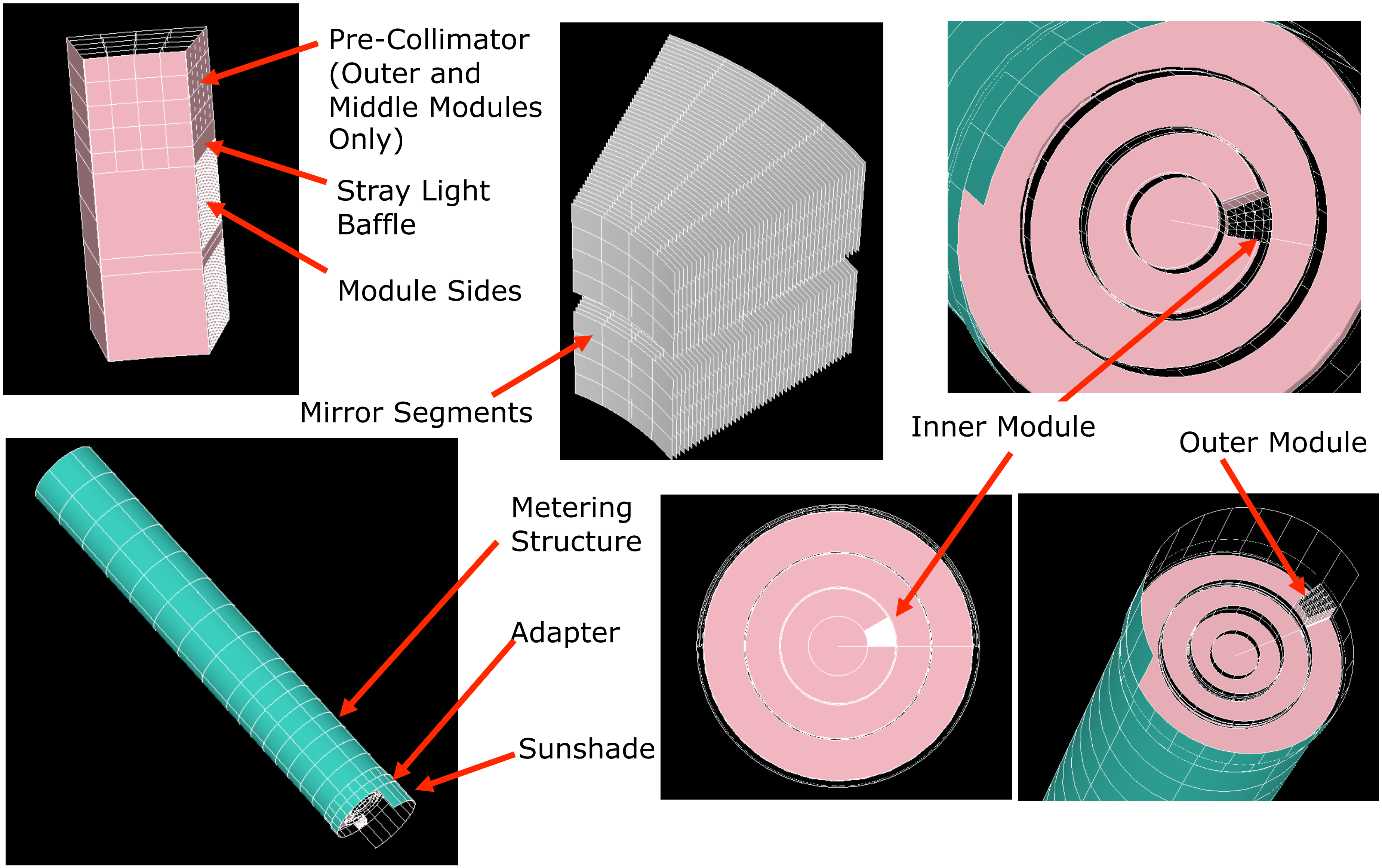
SXT Thermal Design

- Active heater control
  - Multiple heater zones on stray light baffles, module enclosure and section of metering structure adjacent to FMA
- MLI on exterior of metering structure and, as much as possible, adapter
- Cold-biasing FMA to allow active heater control and minimize heater power
  - Conductive silver composite coating (low absorptance and high emittance) on adapter MLI outer cover
    - GGS WIND and POLAR, and IMAGE LENA flight heritage
  - 50% conductive silver composite coating and 50% Germanium Kapton (alternate stripes) on metering structure MLI outer cover
    - Germanium Kapton has Swift BAT flight heritage
  - Conductive silver composite coating on sunshade sun side
- Depth of collimator/stray light baffle affects view of mirror segments to space
  - Significant parameter to be varied

SXT Thermal Modeling/Assumptions

- First step is to ensure sufficient cold biasing for active heater control in worst hot case:
  - Worst hot case stacked parameters:
    - EOL thermo-optical properties (5 year design, 10 year goal)
    - 1418 W/m^2 solar intensity
    - 90° sun angle
    - MLI effective emittance of 0.03
- Second step is to compute heater power in worst cold case:
  - Heater controller set points and heater zones are varied:
    - Length of metering structure with heaters is also varied
  - Worst cold case stacked parameters:
    - BOL thermo-optical properties
    - 1320 W/m^2 solar intensity
    - 70° or 110° sun angle
    - MLI effective emittance of 0.03

SXT Thermal Modeling/Assumptions



SXT Thermal Modeling/Assumptions

- Each mirror module has its own heater control
- Each mirror segment has 16 nodes on each side
- Only one module is included in thermal model at a time for temperature predictions due to very large number of surfaces of all 60 modules and size of radiation couplings:
  - Nearly 5 million radiation couplings for one module and file is larger than 300K KB
  - A different model for inner, middle or outer modules
  - Total heater power is calculated for all 60 modules based on number of modules and heater power for each module
- Mirror is thin glass and coating is iridium:
  - Very low thermal conductivity (~1 Wm-1K-1)
  - Emittance is 0.05 and specular
- Backside of mirror is glass with no coating (high emittance) due to stray light
- Conduction path from mirror segments to module enclosure is very low

SXT Thermal Modeling/Assumptions

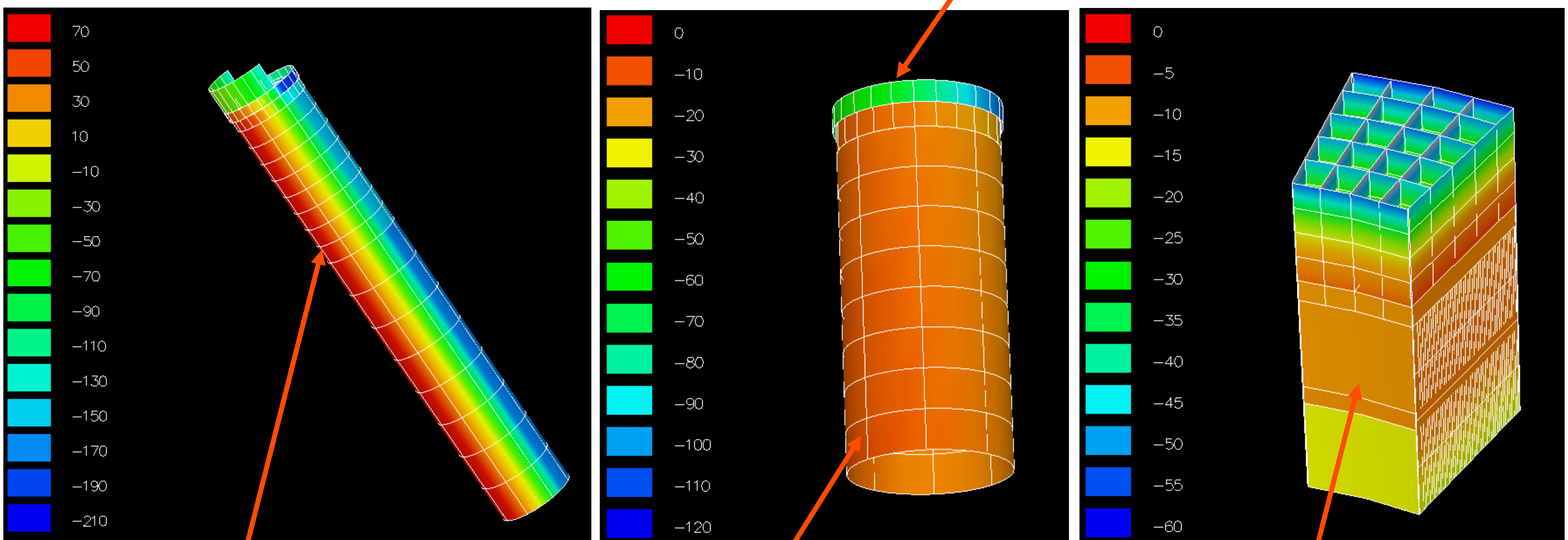
- **Pre-collimator has very low thermal conductivity:**
  - **Fiberglass, G-10, etc.**
- **Interior of metering structure has a high emittance to enhance heat radiation from sun side to anti-sun side**
- **Anti-sun side of sunshade is black Kapton**
- **Heater controllers have ± 0.1°C tolerances or better**

	BOL		EOL (5 Years)	
Coating	Absorptance	Emittance	Absorptance	Emittance
Conductive Silver Composite	0.08	0.60	0.25	0.58
Germanium Kapton	0.45	0.78	0.56	0.76

SXT Thermal Predictions

- In the worst hot case with no active heaters, the module is sufficiently cold-biased

Adapter



MLI

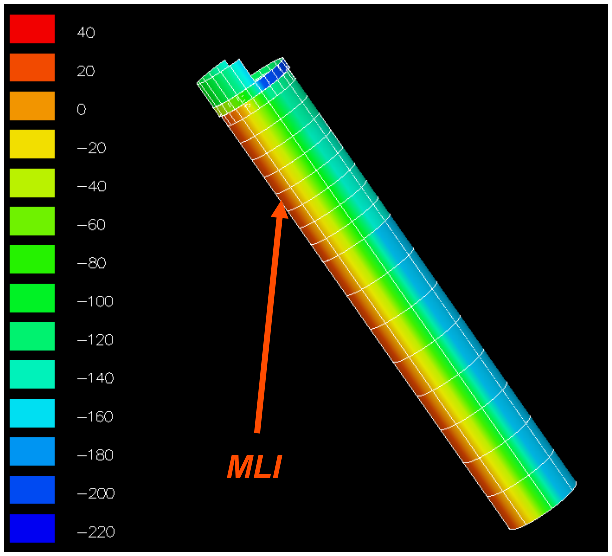
Outer Mirror Module

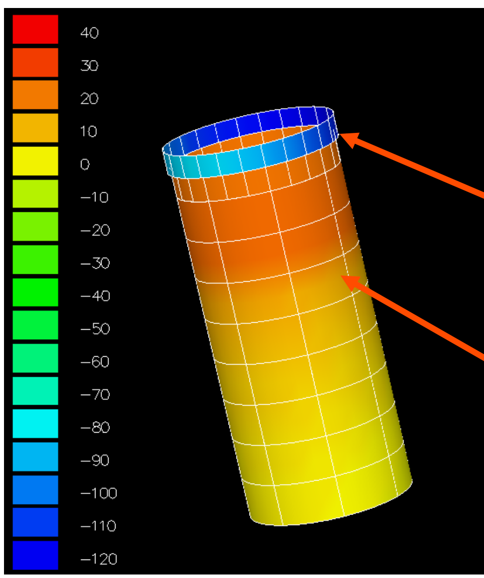
Metering Structure (M55J)

Temperature in °C

SXT Thermal Predictions

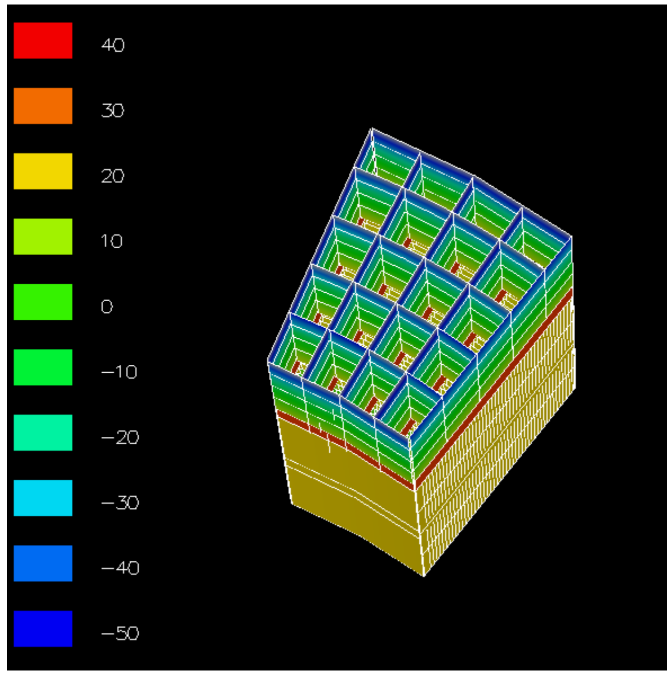
- In the worst cold case with heaters active, the module operating temperature requirement can be met





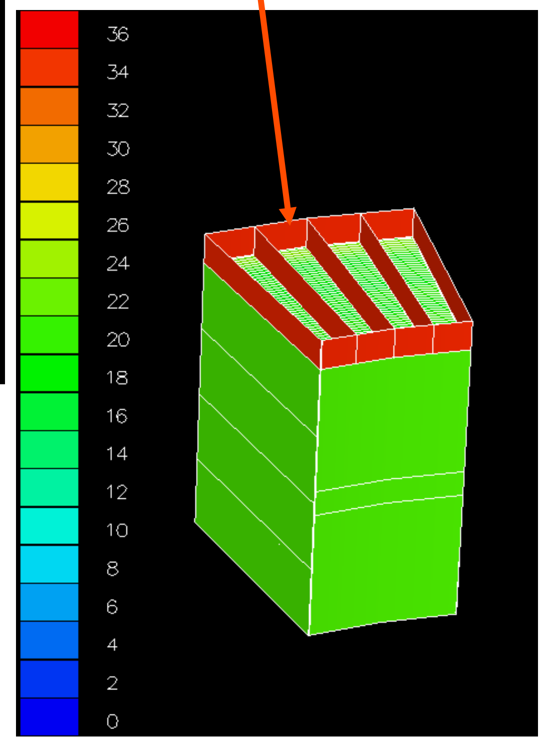
Adapter

Metering Structure (M55J)



Outer Module

Active Heater Control



Temperature in °C

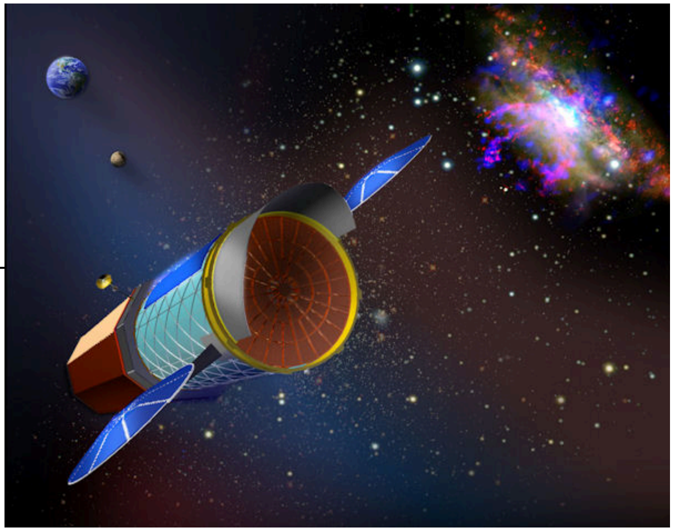
SXT Heater Power Predictions

	Heater Power (W)*
Outer Modules	650
Middle Modules	360
Inner Modules	100**
Metering Structure	420
Total	1530

**BOL worst cold case.*

***A thin aluminized Kapton layer on top of stray light baffle. Aluminum side facing optics.*

FMA Integration and Test



Assumptions

- The passive mounting approach will be used for mirror integration (drives mirror integration order from inner-shell to outer-shell)
- The Thermal Pre-Collimators, Stray Light Baffles, and **Gratings a**re mounted/ aligned to the modules for module-level testing and are not removed afterwards
- Full-aperture X-ray testing will be performed on all modules in a horizontal beam
- Vertical Optical and X-ray testing (pencil-beam) will be performed at the FMA-Level
- The flight FMA structure and flight modules will be acceptance tested / baked-out prior to FMA-Level I&T
- Selection of in-plane Critical Angle Transmission (CAT) gratings (this is a worst-case scenario for FMA flow, as there is no interface/impact to the FMA for off-plane gratings)

FMA Development Flow

Pre-Phase A-to-Phase A

Technology Development →

- Develop methods and processes required to meet requirements and TRL levels

Phase A-to-CDR

(A) FMA Design and Test →

- Optimize the designs and processes to meet requirements for flight - perform testing
- SXT Modules
- FMA Structure

Post-CDR

(B) FMA Integration and Test →

- Build, assemble, and test flight hardware to meet requirements for flight
- SXT Modules
- HXMM Module

FMA-to-Observatory Integration and Test

- Mate the FMA with the Observatory and Test

A - FMA Design and Test - Engineering Test Units (ETU's)

Engineering Test Units

Further develop and test the Module design and optical testing processes and equipment

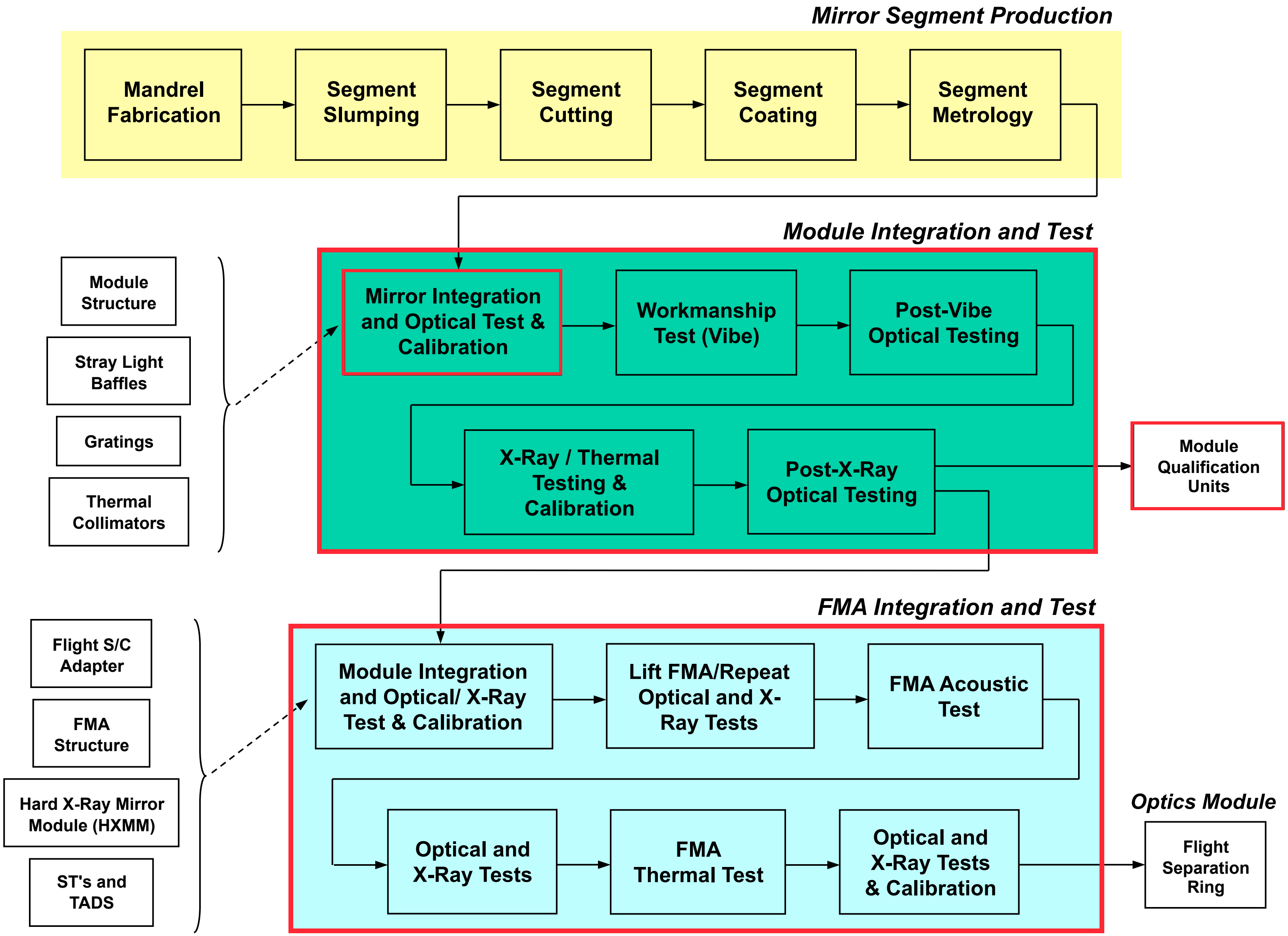
Module ETU

- **One inner- and one outer-module ETU:**
  - **Only a few optical-quality segments**
  - **Balance of segments will be mass dummies**
- **Refine segment integration techniques, including optical testing configurations**
- **Perform full aperture X-ray testing**
- **Perform mechanical, thermal, optical, and long term stability**

FMA Structure ETU (Sub-Scale)

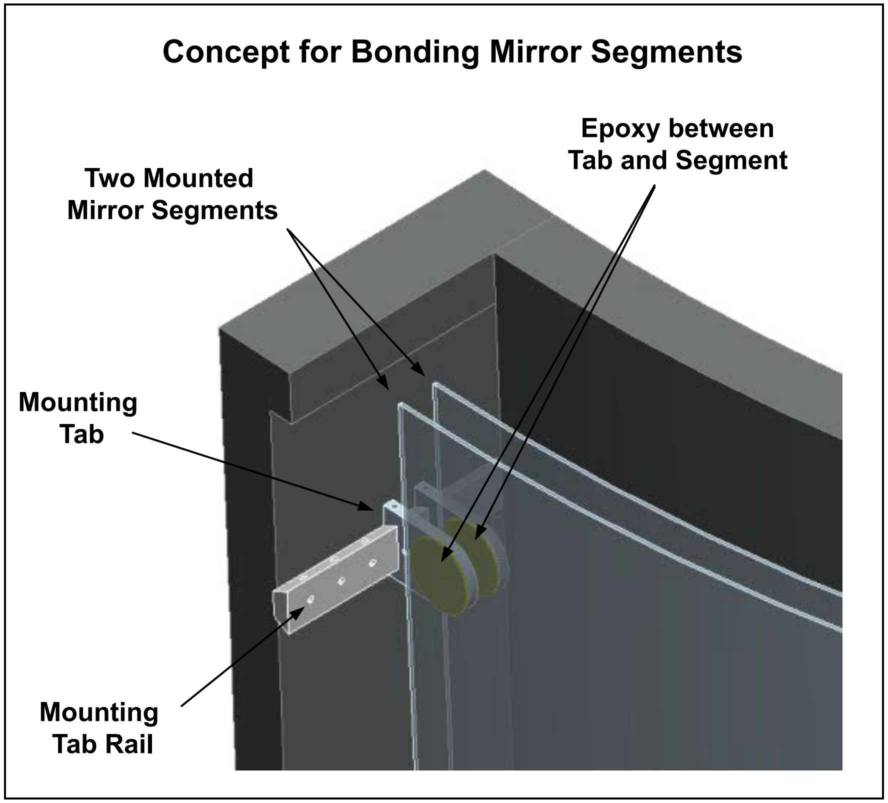
- **Not a full-scale build**
- **Sub-scale models**
- **Joint tests**
- **Materials testing**
- **Alignment tests**

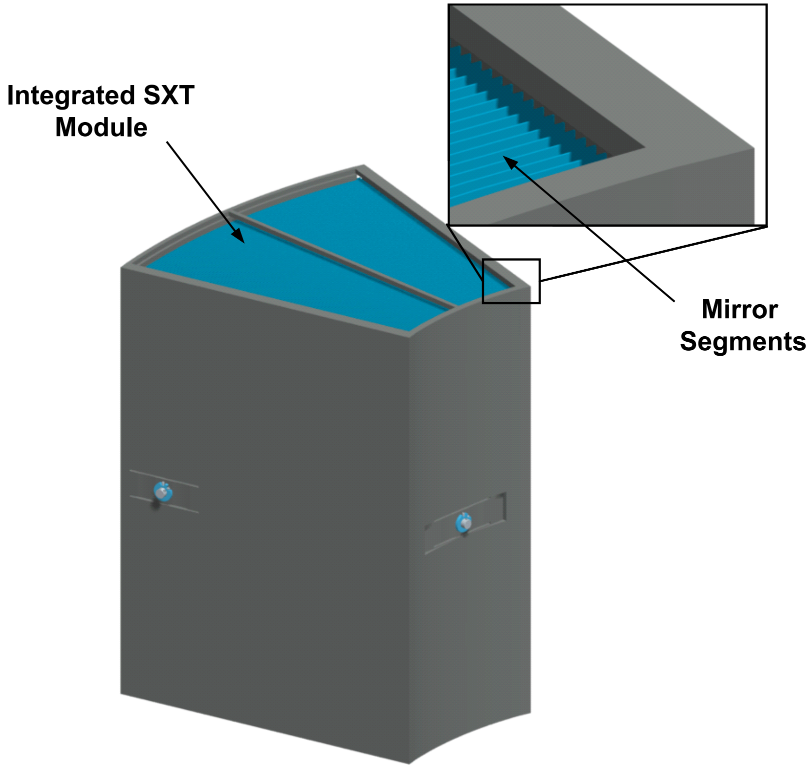
B - FMA Integration and Test Flow



SXT Module Integration & Test

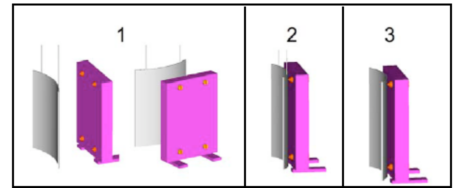
- Includes the steps required to align and integrate mirror segment pairs into the SXT modules and fully test the integrated modules:
  - Utilizes Suspension Mount process to hold and position segments
  - Utilizes Hartmann Test to align segments
- Segment installation order is from the inner-to-outer shell





SXT Mirror Integration and Optical Test Flow

Suspension Mount Process - Temporary Mount



Temporary Mount

Mirror Segments → Bond Suspension Wires & Cure → Suspend Segment → Bond to Temporary Mount/Cure → Segment Metrology → Analysis - Pass/Fail

Permanent Mount

Modules → Module/Optical Reference Metrology → Install and Align a Segment → Optical Test of Segment (Hartmann Test) → Bond the Segment

→ Repeat the Previous 3 Steps for the Remaining Segments → Install Module Closeout Panels → Perform Throughput Test → Install and Align the Stray Light Baffle

→ Repeat the Throughput and Hartmann Test → Install and Align the Thermal Pre-Collimators / Thermal Shield → Repeat the Throughput and Hartmann Test

SXT Module Integration and Test - Test Plan

- Optical metrology will be used to establish references and monitor stability of hardware
- Optical testing:
  - Mirror alignment via Hartmann test
  - Focus/Image test
  - Throughput test (obscuration measurement)
- Workmanship vibe - 4 modules at a time
- X-Ray test (X-Ray Calibration Facility (XRCF) at MSFC):
  - 2 modules in chamber at a time (one tested at a time, with the other masked)
  - Point Spread Function (PSF) and Effective Area
  - Stray light test
  - Heater function and thermal gradient test
  - Additional calibration tests
  - Gratings testing

FMA/SXT Qualification Unit (QU) Testing

- **One fully-tested module per ring will be assigned as a qualification test unit (to be tested in parallel with the FMA I&T)**

Qualification Units

- **Fully test and qualify the flight designs**
- **Done in parallel with flight I&T**

Module QU

- **The first flight modules off of the production line for each ring (1 inner-, 1 middle-, 1 outer-module)**
- **Modal survey**
- **Acoustic test**
- **Vibe test**
- **Thermal test**
- **Movement/repeatability test**

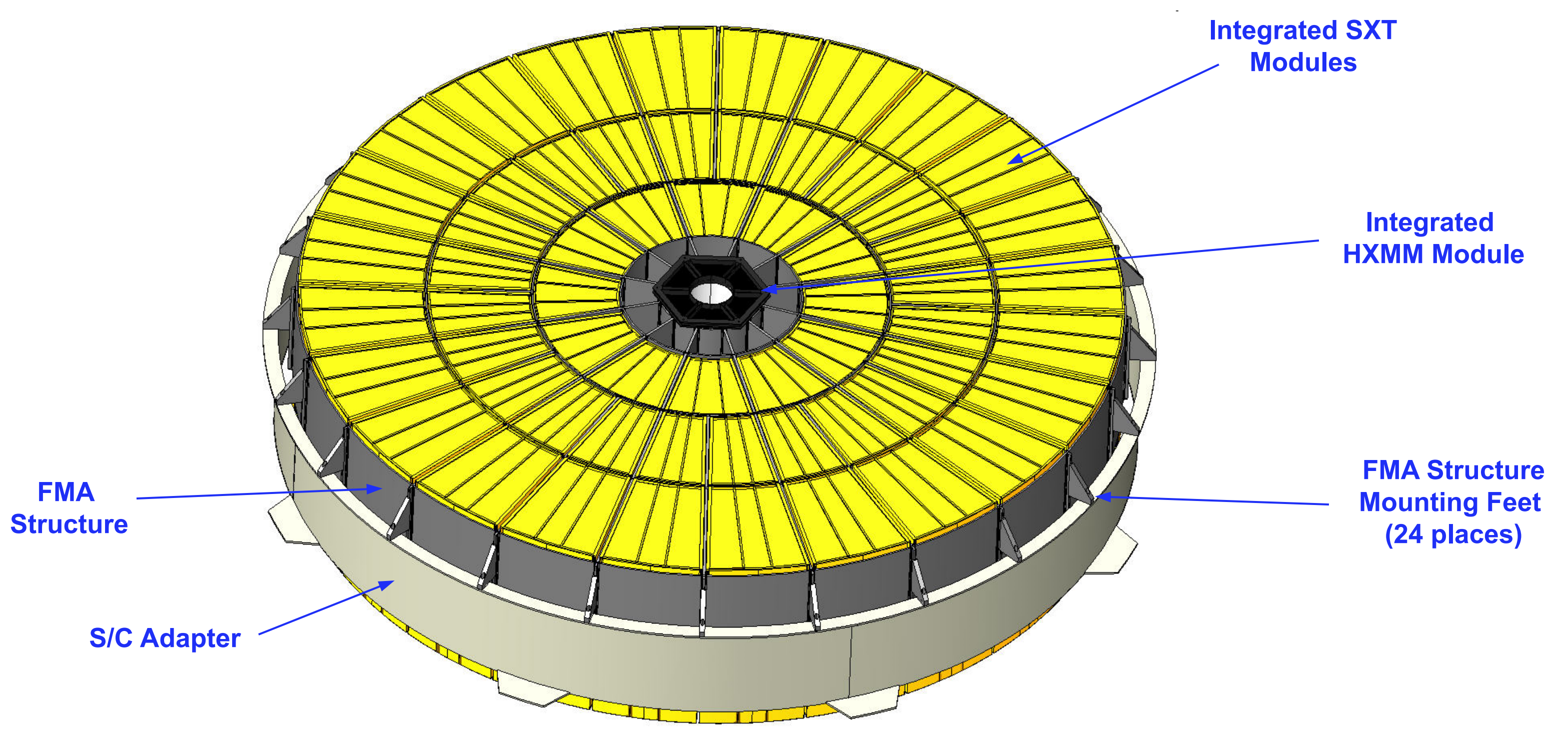
FMA Structure QU

- **Built in parallel with the flight FMA structure**
- **Modal survey**
- **Static load test**
- **Acoustic test/shock test**
- **Thermal test**
- **Facility/GSE fit-checks**

Note: QU's will not be flight units/spares, due to accumulated testing loads

FMA-Level Integration and Test - Mechanical Configuration

- The FMA Structure will be attached to the Optics Module (S/C Adapter)
- The S/C Adapter/FMA structure will be supported by g-negation GSE (not shown)
- Module mass dummies will populate each empty module cell
- SXT modules are integrated from above (easier access to mounting hardware)
- HXMM integrated from above



FMA-Level Integration and Test - Vertical Optical/X-Ray Facility

- Optical testing
- X-ray testing
- Sized to accommodate 20 m focal length

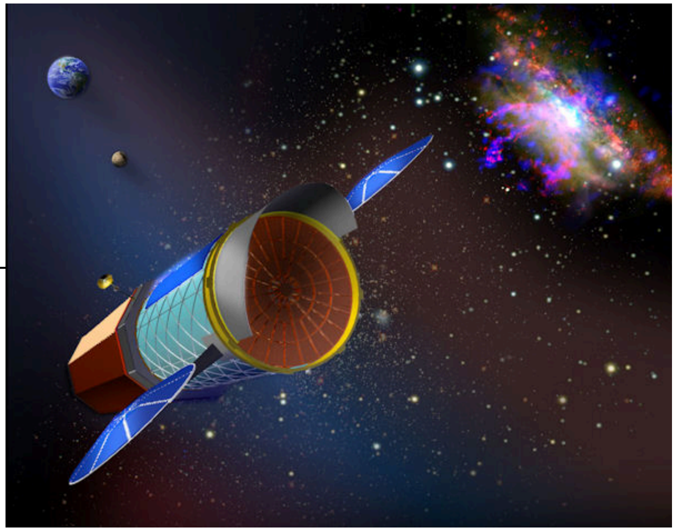
Considerations for Module Integration

- **Module Alignment:**
  - Modules are sensitive to translation:
    - The focus and image move as the module is translated
  - Modules are less sensitive to tilt:
    - A module acts like a thin lens - the focal point does not shift, but throughput is reduced as the module is tilted
    - Point spread function (PSF) worsens with tilt
- **Distortions:**
  - Module:
    - For a closely matched structure (0.2 ppm/°C mismatch), sensitivity is 0.6 arc-sec HPD per °C bulk temperature change
    - For a radial temperature gradient, sensitivity is 1.6 arc-sec HPD per °C gradient
    - For an axial (most likely to occur) temperature gradient, sensitivity is 0.1 arc-sec HPD per °C gradient
  - FMA structure - modules will be isolated from the primary structure via flexures

FMA-Level Integration and Test - Test Plan

- Modules are integrated from the inner-ring outwards
- Optical test:
  - Verify SXT module alignment and focus
  - Tilt the Temporary Mount to establish the proper cone angle for each segment
- Close facility door and pump-down for X-ray testing:
  - Verify the system effective area, PSF, calibration
  - Additional grating testing
- Alternate between Optical and X-ray testing as SXT modules are integrated and aligned (limited number of X-ray tests - not after each SXT module)
- HXMM alignment determined via optical telescope measurements and verified via X-ray test (not done via optical test)
- Thermal Testing:
  - Verify heater function
  - Set up thermal gradients across the FMA and modules to verify requirements
  - Verify heaters at survival temperature
- Mate the Separation Ring with the FMA after testing to form the Optics Module configuration
- Rastering pencil-beam source will also be used at the Observatory-Level to stimulate flight Instruments with X-rays

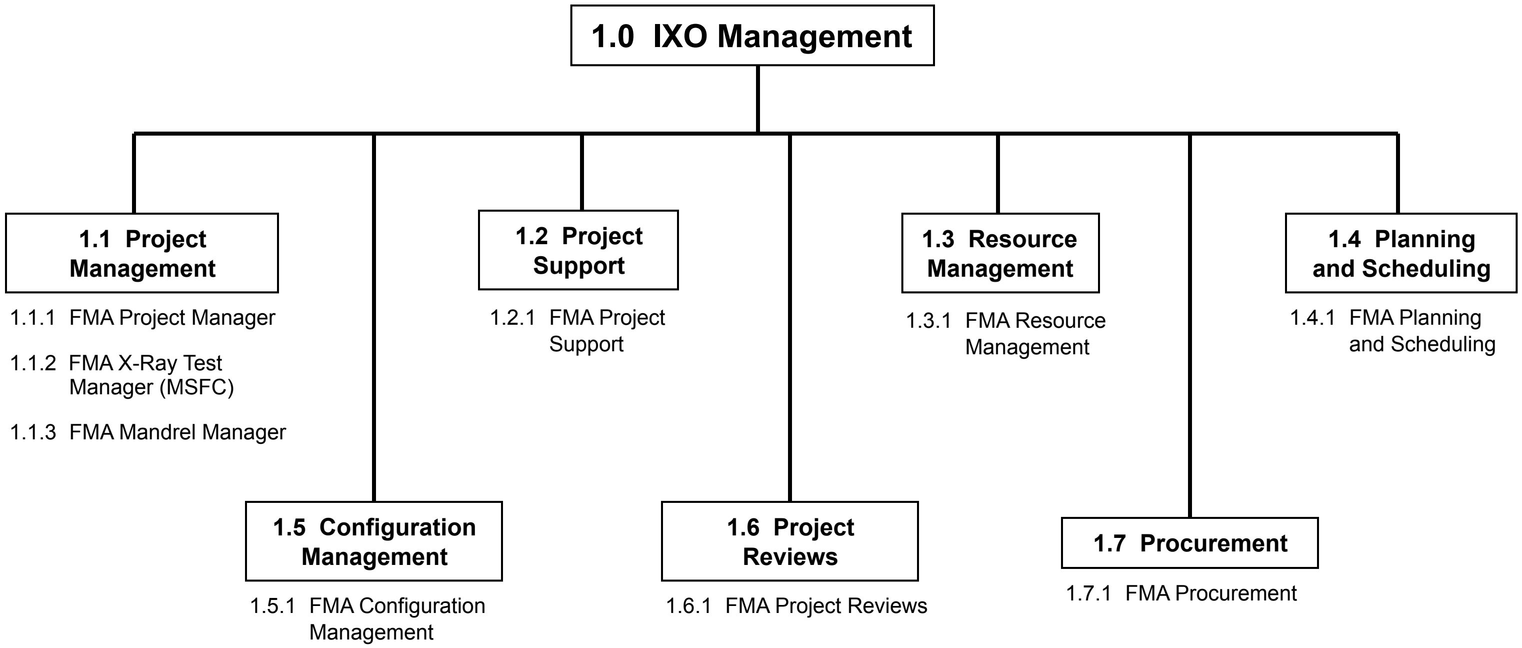
FMA Cost Estimates, Schedules, and Process Flows



FMA Cost Estimates

- **A cost estimate for the Flight Mirror Assembly (FMA) has been developed using grass roots methodology, and has been validated by PRICE-H:**
  - Based on a Work Breakdown Schedule (WBS) developed for the FMA
  - Based on FMA schedules developed to track the FMA development, design, build, and test phases
  - Based on the FMA process flows developed to detail the specific processes and the personnel/facilities that are required
  - Based on Basis of Estimates (BOE's) developed for each FMA WBS
  - Phased manpower and materials estimates are based on:
    - A preliminary design supported by CAD, structural, and thermal/optical analyses to determine material selection and sizing
    - The modular nature of the FMA, which has 24 identical outer modules, 24 identical middle modules, and 12 identical inner modules, was accounted for in the costing
    - The mirror segment production portion of the cost estimate is based on NuSTAR's experience-to-date for establishment of mirror production facilities and fabrication of flight mirror segments

FMA WBS


1.0 IXO Management
1.1 Project Management
1.1.1 FMA Project Manager
1.1.2 FMA X-Ray Test Manager (MSFC)
1.1.3 FMA Mandrel Manager
1.2 Project Support
1.2.1 FMA Project Support
1.3 Resource Management
1.3.1 FMA Resource Management
1.4 Planning and Scheduling
1.4.1 FMA Planning and Scheduling
1.5 Configuration Management
1.5.1 FMA Configuration Management
1.6 Project Reviews
1.6.1 FMA Project Reviews
1.7 Procurement
1.7.1 FMA Procurement

FMA WBS (cont'd)

- **2.0 Systems Engineering**
  - **2.1 Mission and Instrument Systems Interfaces**
    - 2.3.1 FMA Mission and Instrument Systems Interfaces
  - **2.2 Risk Management**
    - 2.4.1 FMA Risk Management
  - **2.3 Instrument Systems Engineering**
    - 2.3.1 FMA Systems Engineering
  - **2.4 Instrument Contamination Control**
    - 2.4.1 FMA Contamination Control
  - **2.5 Mechanical Systems Engineering**
    - 2.5.1 FMA Mechanical Systems Engineering
  - **2.6 Instrument Thermal Systems**
    - 2.6.1 FMA Thermal Systems
  - **2.9 Instrument Materials**
    - 2.9.1 FMA Materials

- **3.0 Safety and Mission Assurance**
  - **3.2 System Safety**
    - 3.2.1 FMA System Safety
  - **3.3 Quality Assurance**
    - 3.3.1 FMA Quality Assurance
  - **3.4 Reliability Analysis**
    - 3.4.1 FMA Reliability Analysis
  - **3.6 Parts Engineering**
    - 3.6.1 FMA Parts Engineering

FMA WBS (cont'd)

4.0 Science & Technology

4.1 Soft X-Ray Telescope (SXT) Mirror Technology Development

4.1.1 Management

- 4.1.1.1 GSFC Management
- 4.1.1.2 SAO Management
- 4.1.1.3 MSFC Management

4.1.2 Mirror Segment Fabrication

- 4.1.2.1 Slumping
- 4.1.2.2 Cutting
- 4.1.2.3 Coating
- 4.1.2.4 Metrology
- 4.1.2.5 Inspection

4.1.3 Mirror Alignment & Mount Development

- 4.1.3.1 Suspension Mount Method
  - 4.1.3.1.1 Temporary Mount
  - 4.1.3.1.2 Permanent Mount
    - 4.1.3.1.2.1 Mirror Housing Simulator
    - 4.1.3.1.2.2 Mini-Module
  - 4.1.3.1.3 Optical Test
  - 4.1.3.1.4 X-Ray Test
  - 4.1.3.1.5 Environmental Test
- 4.1.3.2 Optical Alignment Pathfinder (OAP) Method
  - 4.1.3.2.1 Permanent Mount
  - 4.1.3.2.2 Optical Test
  - 4.1.3.2.3 X-Ray Test
  - 4.1.3.2.4 Environmental Test

4.1.4 Mirror Module Prototype Development

- 4.1.4.1 Inner Module Prototype
- 4.1.4.2 Outer Module Prototype

FMA WBS (cont'd)

5.0 Payload

5.1 Formed Glass Optics Flight Mirror Assembly (FGO-FMA)

5.1.1 Management

- 5.1.1.1 PM + deputy
- 5.1.1.2 Resource Management
- 5.1.1.3 Procurement
- 5.1.1.4 Travel
- 5.1.1.5 Reviews
- 5.1.1.6 Configuration Management
- 5.1.1.7 Planning and Scheduling
- 5.1.1.8 Administrative Support
- 5.1.1.9 Training

5.1.2 Systems

- 5.1.2.1 Systems
  - 5.1.2.1.1 Error budgets
  - 5.1.2.1.2 Interface control
- 5.1.2.2 Optical
  - 5.1.2.2.1 Design
  - 5.1.2.2.2 Analysis
- 5.1.2.3 Thermal
- 5.1.2.4 Contamination
- 5.1.2.5 Electrical
- 5.1.2.6 Mechanical

5.1.3 S&MA

- 5.1.3.1 System Safety
- 5.1.3.2 Quality Assurance
- 5.1.3.3 Reliability
- 5.1.3.4 Materials

5.1.4 Mandrels

- 5.1.4.1 Production Management
- 5.1.4.2 Shipping

5.1.5 Mirror Segments

- 5.1.5.1 Production Management
- 5.1.5.2 Production Lines
  - 5.1.5.2.1 Plan, design, build
- 5.1.5.3 Fabrication
  - 5.1.5.3.1 Slumping
  - 5.1.5.3.2 Cutting
  - 5.1.5.3.3 Coating
- 5.1.5.4 Metrology
- 5.1.5.5 Inspection
- 5.1.5.6 GSE
- 5.1.5.7 Shipping

5.1.6 Structures

- 5.1.6.1 Primary Structure
  - 5.1.6.1.1 Design and Analysis
  - 5.1.6.1.2 ETU
  - 5.1.6.1.3 Qualification
  - 5.1.6.1.4 Flight
  - 5.1.6.1.5 GSE
  - 5.1.6.1.6 Shipping
- 5.1.6.2 Mirror Module Structure
  - 5.1.6.2.1 Design and Analysis
  - 5.1.6.2.2 ETU
  - 5.1.6.2.3 Qualification
  - 5.1.6.2.4 Flight
  - 5.1.6.2.5 Stray Light Baffle
  - 5.1.6.2.6 Thermal Pre-Collimator
  - 5.1.6.2.7 GSE
  - 5.1.6.2.8 Shipping

5.1.7 Thermal Hardware

- 5.1.7.1 Heaters
- 5.1.7.2 Controllers
- 5.1.7.3 Thermisters
- 5.1.7.4 Harness
- 5.1.7.5 EGSE

5.1.8 Flight Module I&T

- 5.1.8.1 Module I&T Management
- 5.1.8.2 Production lines
  - 5.1.8.2.1 Design, procure, build
- 5.1.8.3 Module X-ray test design/ upgrade
  - 5.1.8.3.1 Plan, design, procure, build
- 5.1.8.4 Prep Module structure
  - 5.1.8.4.1 Thermal HW integration
  - 5.1.8.4.2 Baseline metrology
- 5.1.8.5 Integrate Module
  - 5.1.8.5.1 Align, bond, optical test
  - 5.1.8.5.2 Integ. & align SLB & TPC, optical test
- 5.1.8.6 Vibe Test (4 at a time), optical test
- 5.1.8.7 X-ray test @ MSFC, optical test
- 5.1.8.8 GSE
- 5.1.8.9 Shipping
- 5.1.8.10 Contamination

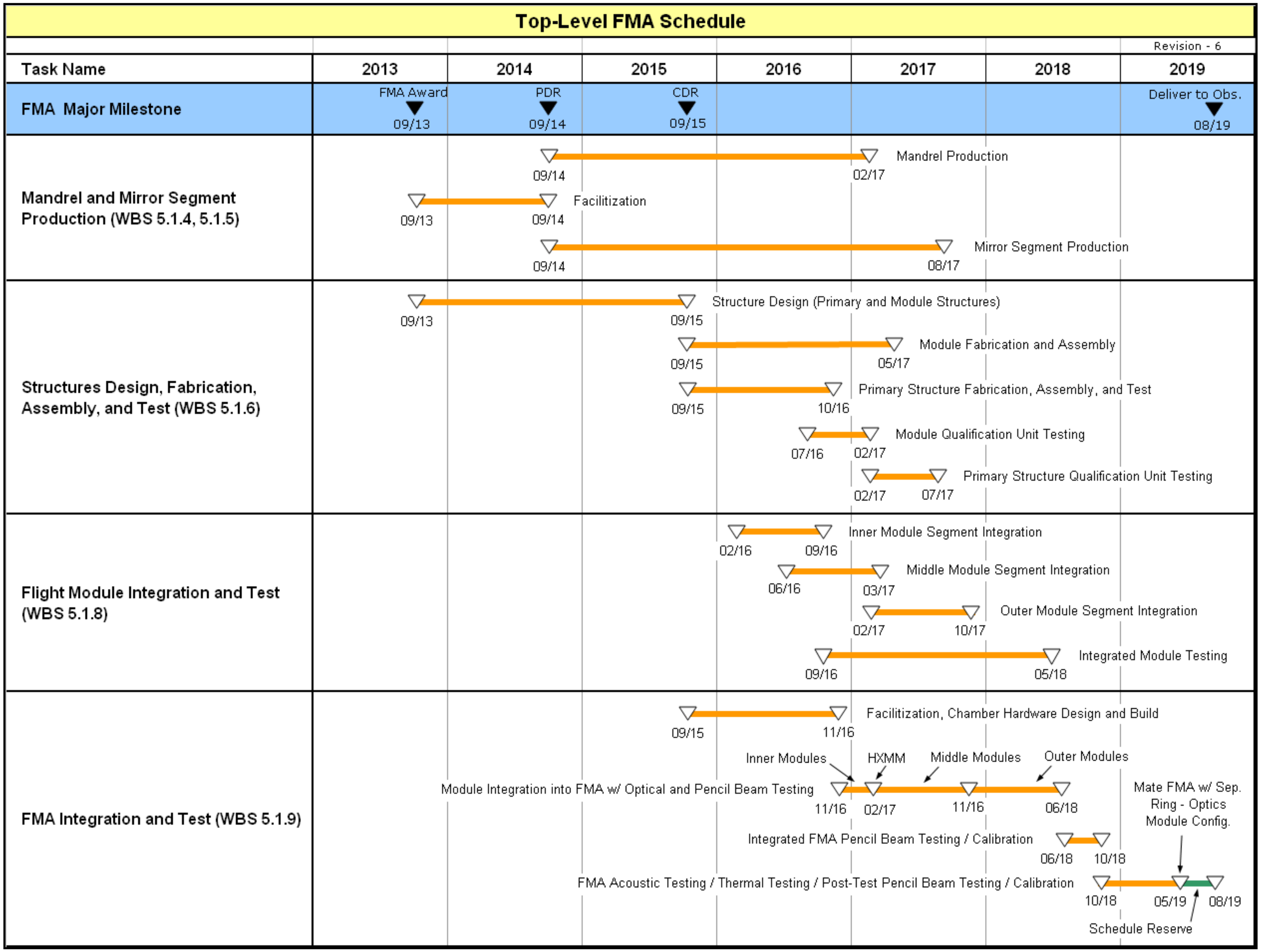
5.1.9 Flight FMA I&T

- 5.1.9.1 FMA I&T Management
- 5.1.9.2 Optical / X-ray Test Planning
  - 5.1.9.2.1 Plan, design, build
- 5.1.9.3 Optical acceptance test module
- 5.1.9.4 Prepare primary structure
- 5.1.9.5 Integrate module to FMA
- 5.1.9.6 Optical test
- 5.1.9.7 X-ray test
- 5.1.9.8 Environmental
- 5.1.9.9 GSE
- 5.1.9.10 Shipping
- 5.1.9.11 Contamination

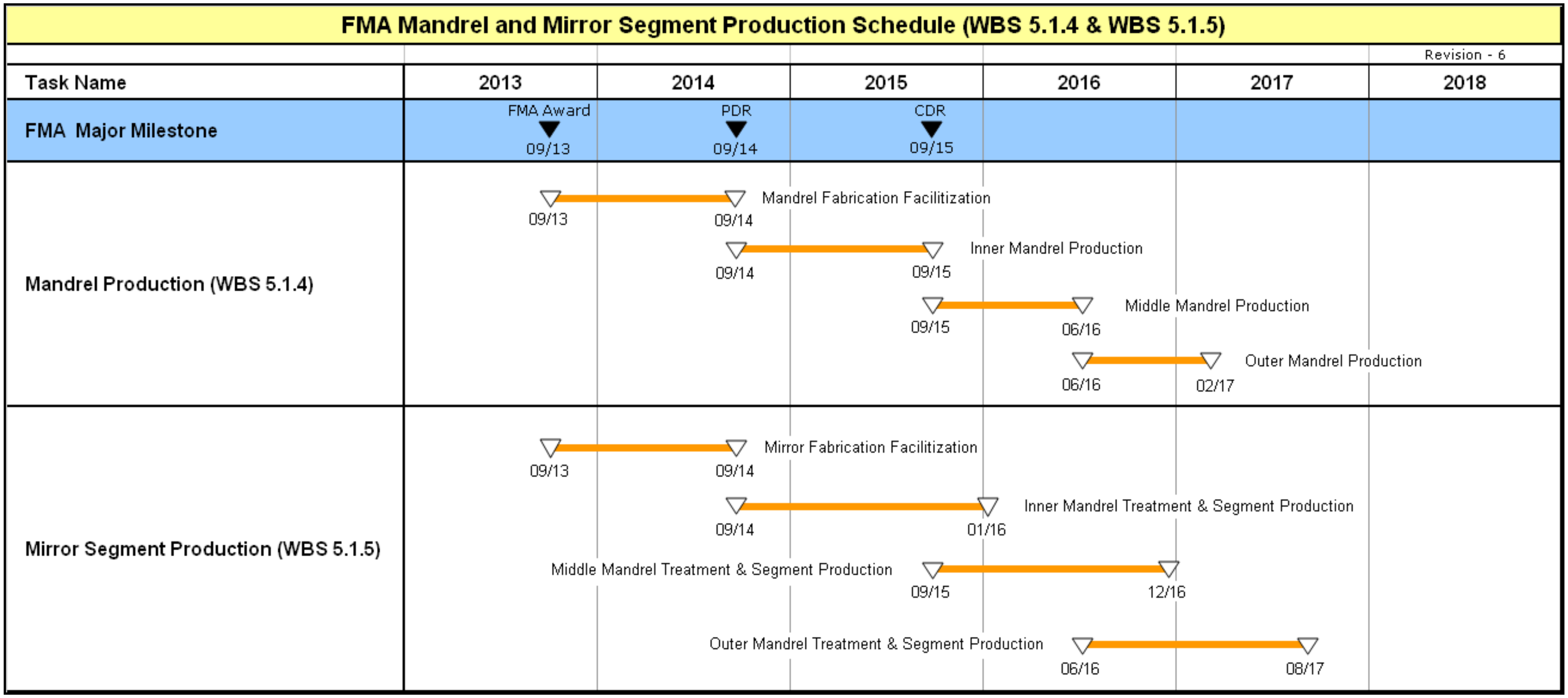
5.1.10 HXMM

- 5.1.10.1 Mirror Production Management
- 5.1.10.2 Shipping

Top-Level FMA Schedule

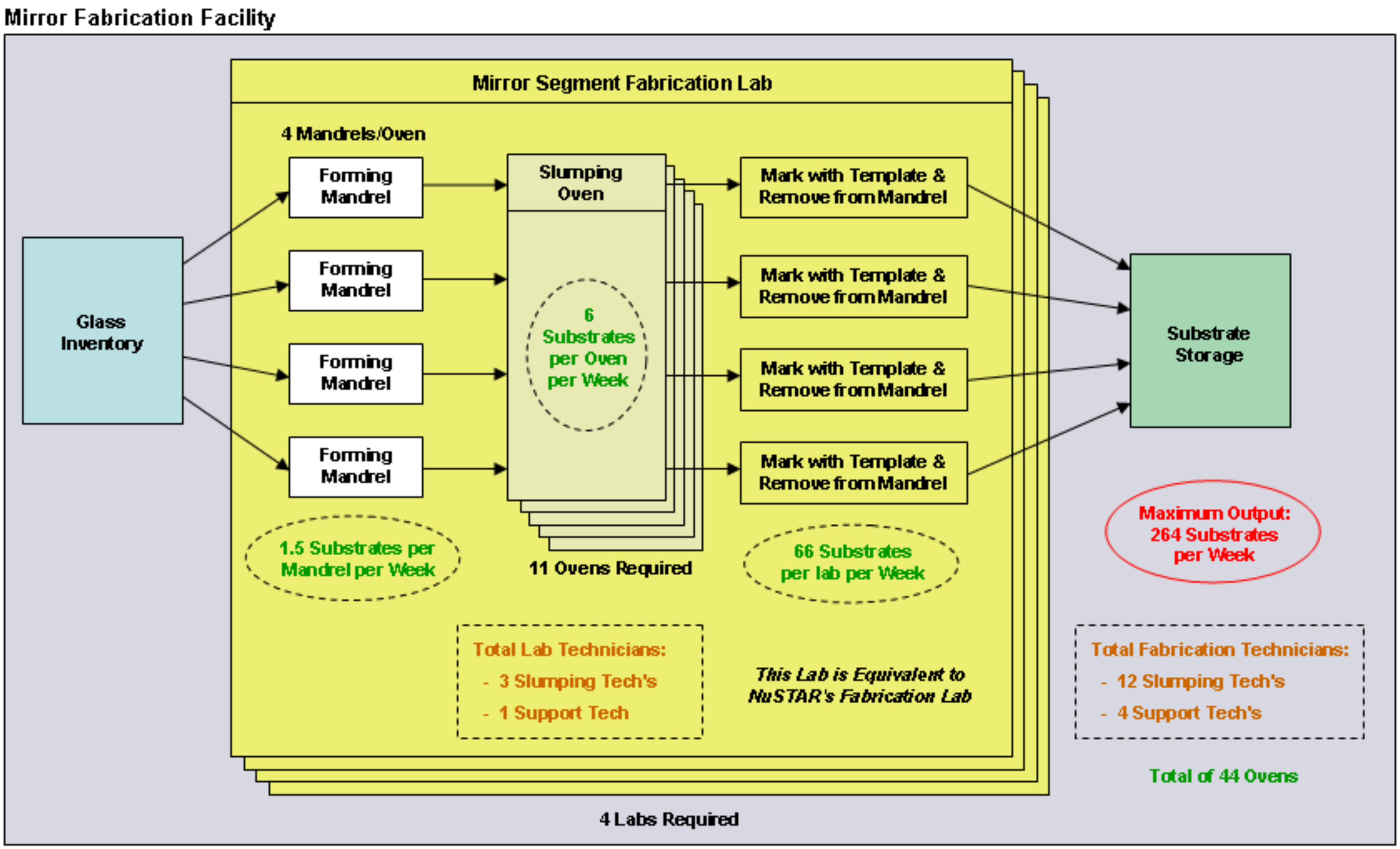


FMA Mandrel and Mirror Segment Production Schedule



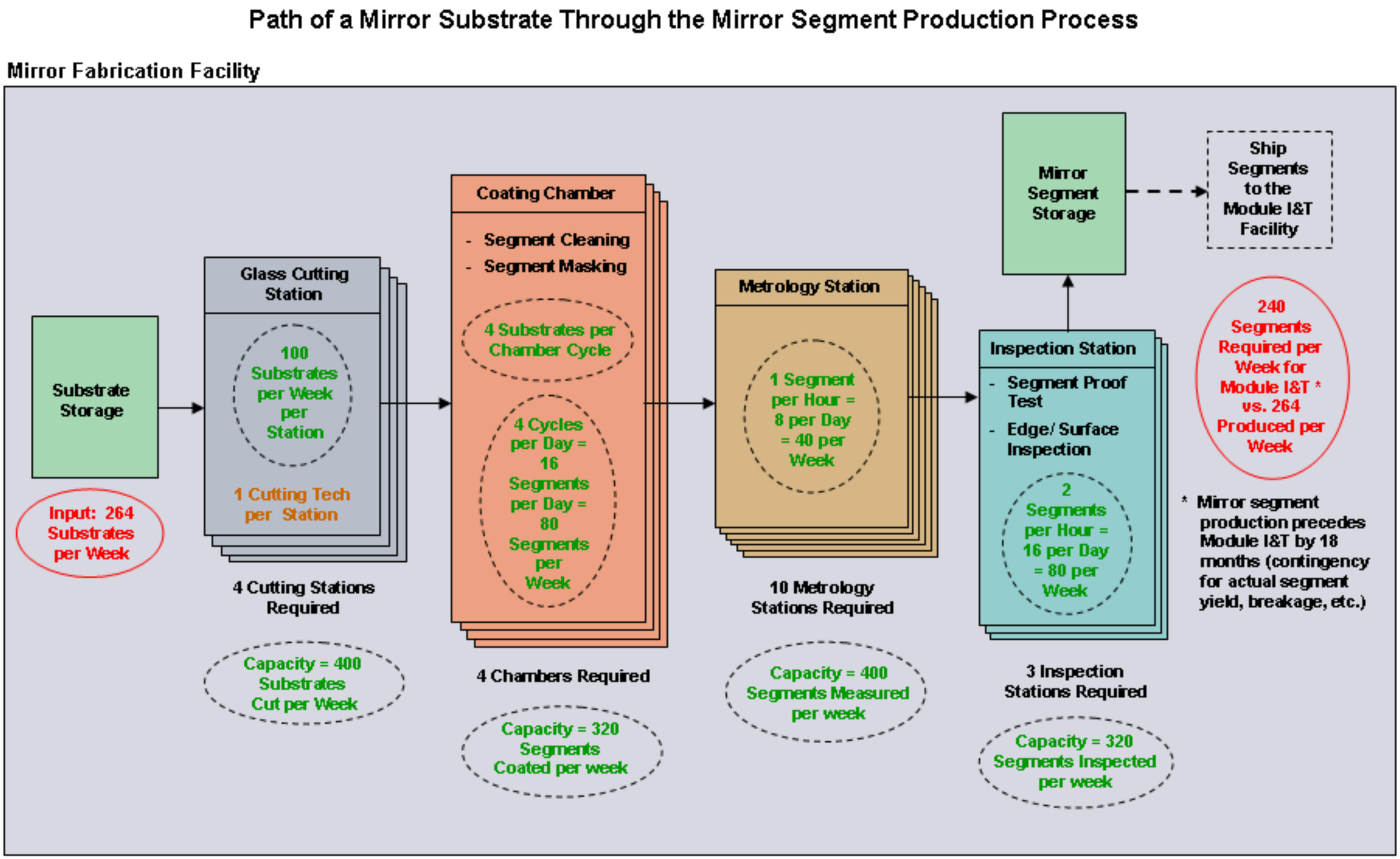
FMA Mirror Substrate Fabrication Flow

Path of a Mirror Substrate Through the Substrate Fabrication Process



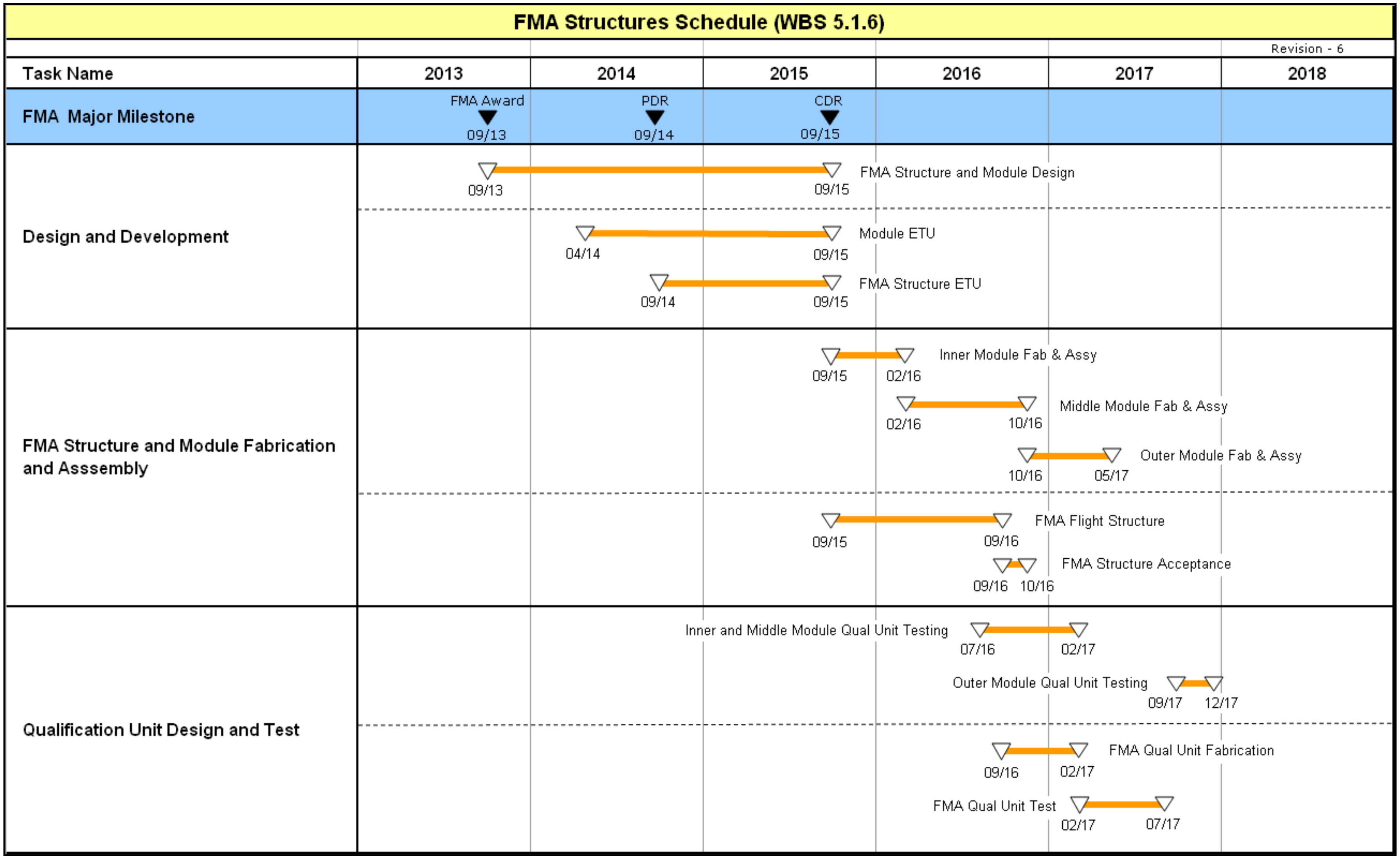
Note: The process flow and production rates have been demonstrated by actual NuSTAR and IXO production

FMA Mirror Substrate Fabrication Flow (cont'd)

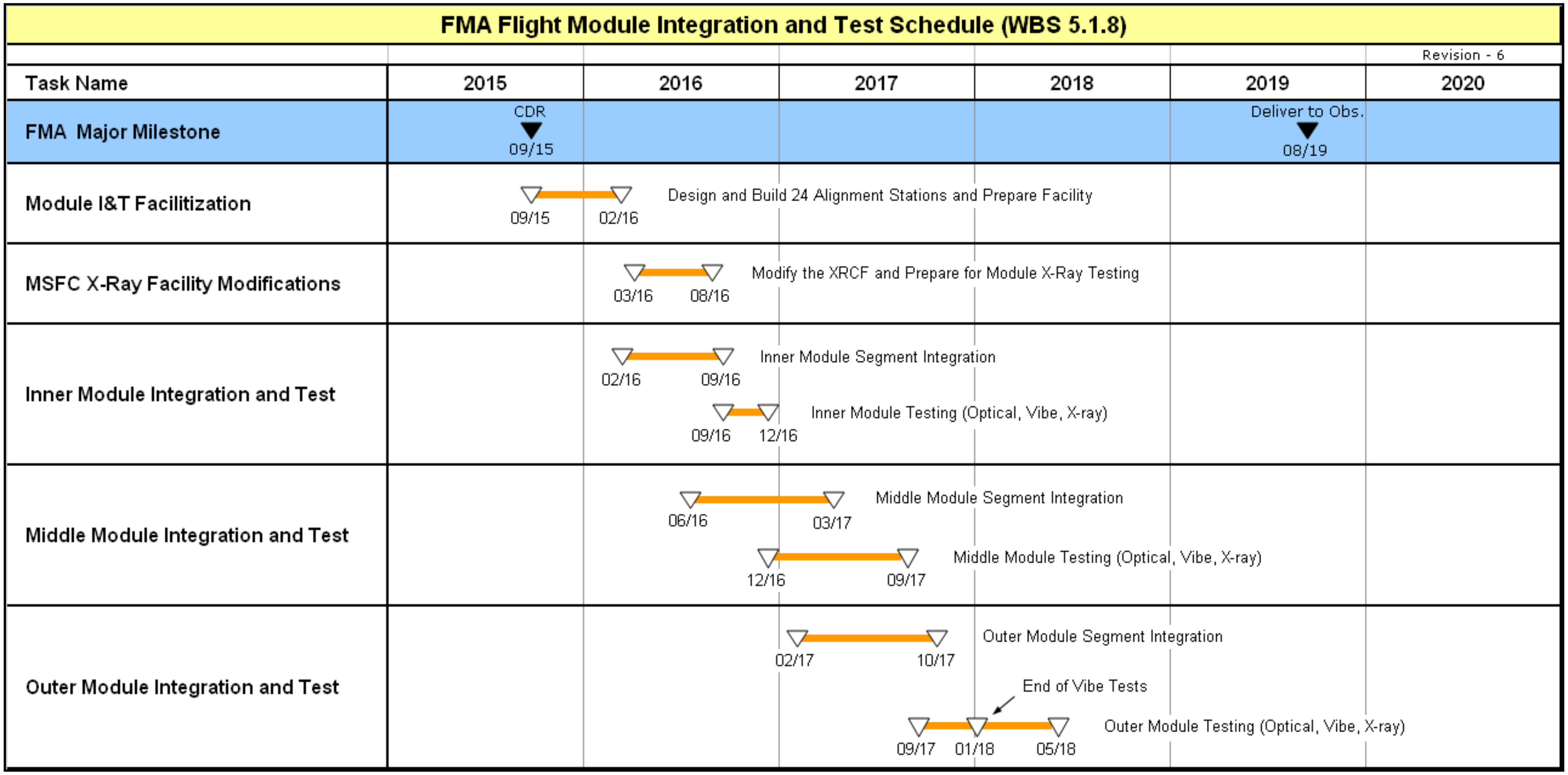


Note: The process flow and production rates have been demonstrated by actual NuSTAR and IXO production

FMA Structures Schedule



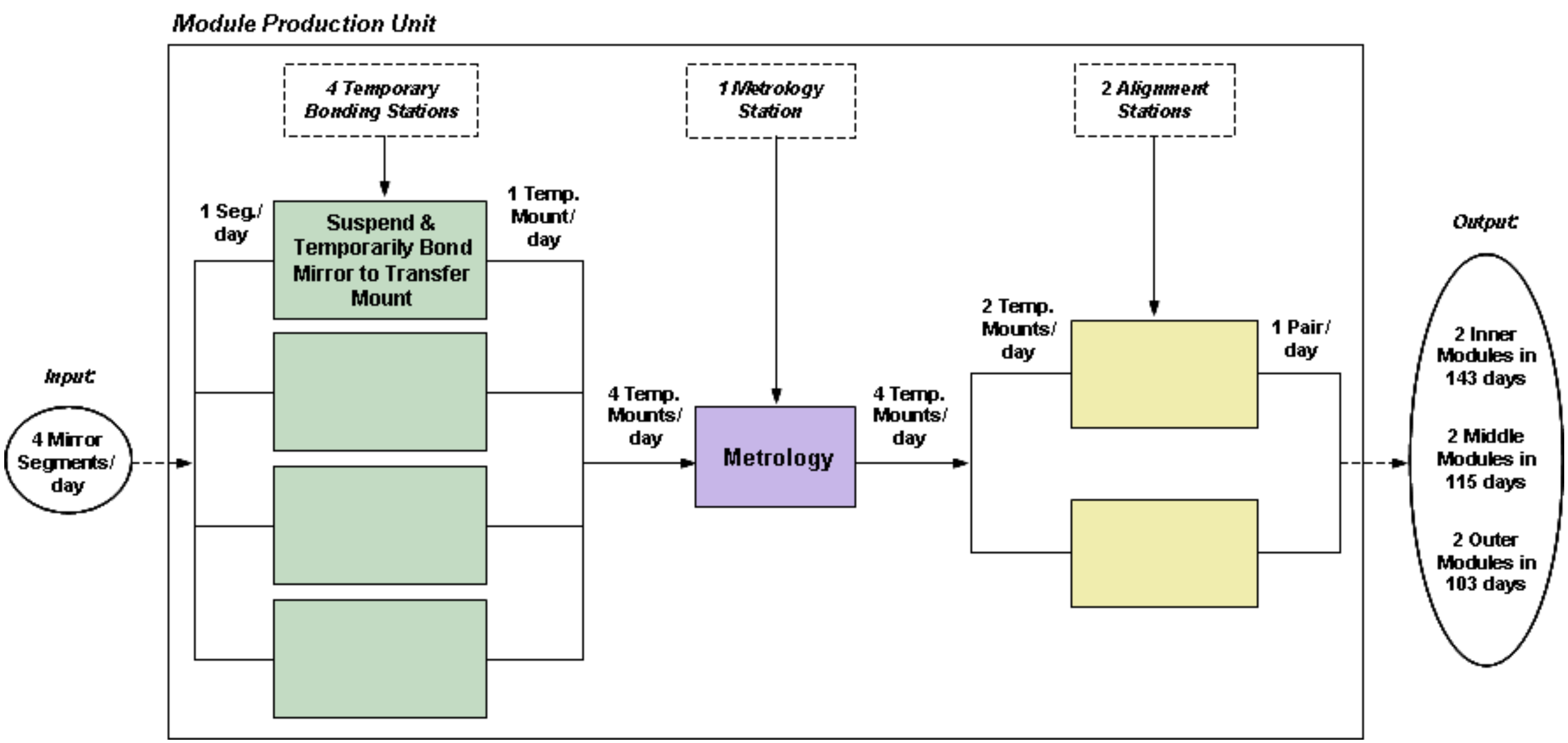
FMA Flight Module Integration and Test Schedule



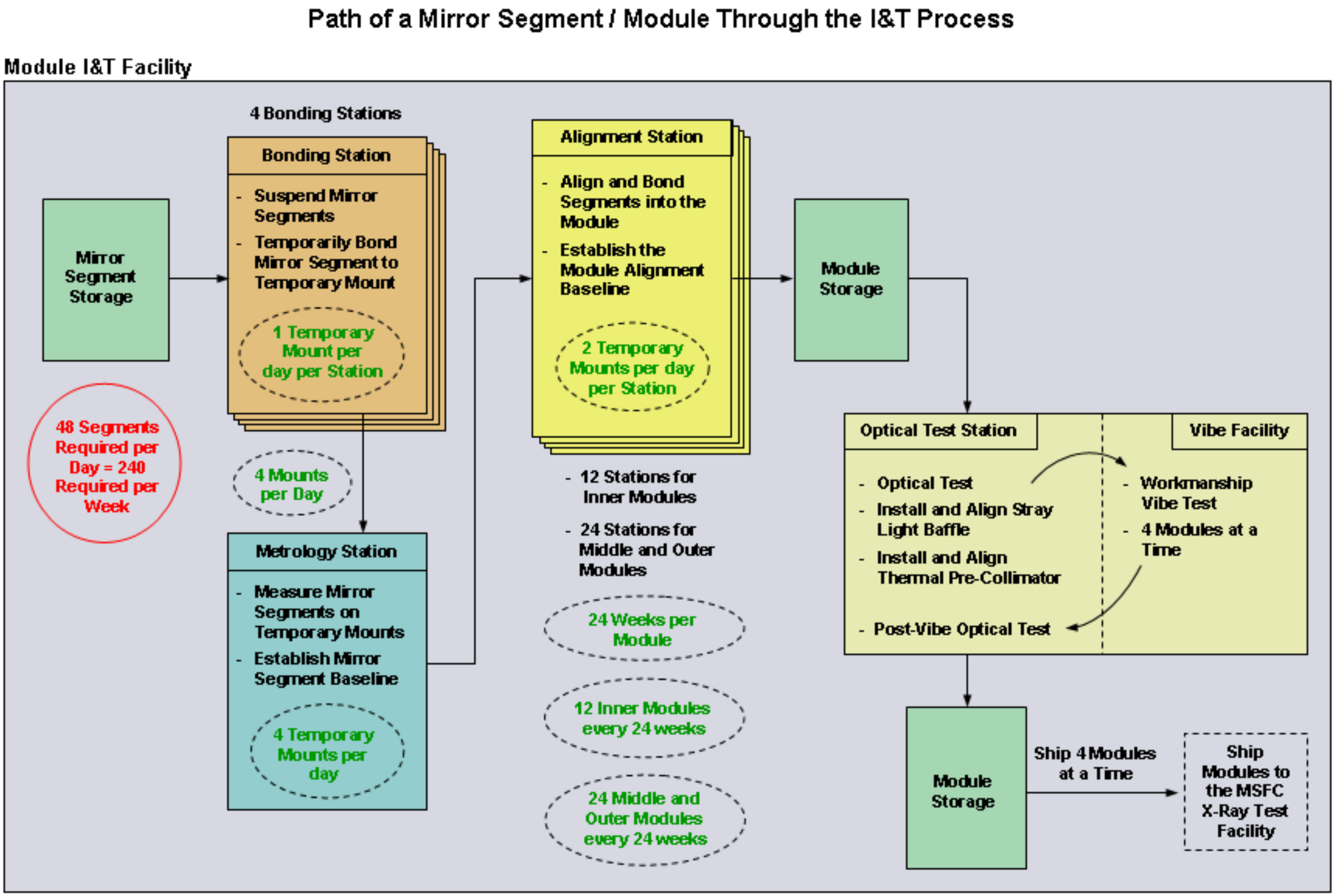
FMA Mirror Segment Bonding and Alignment Production Rate

- **Based on current technology development:**
  - A Module Production Unit defines the minimum block of infrastructure needed
    - 12 inner modules in minimum time (143 pairs = 143 days + test time) = 6 Module Production Units
    - 24 middle modules in minimum time (115 pairs = 115 days + test time) = 12 Module Production Units
    - 24 outer modules in minimum time (103 pairs = 103 days + test time) = 12 Module Production Units

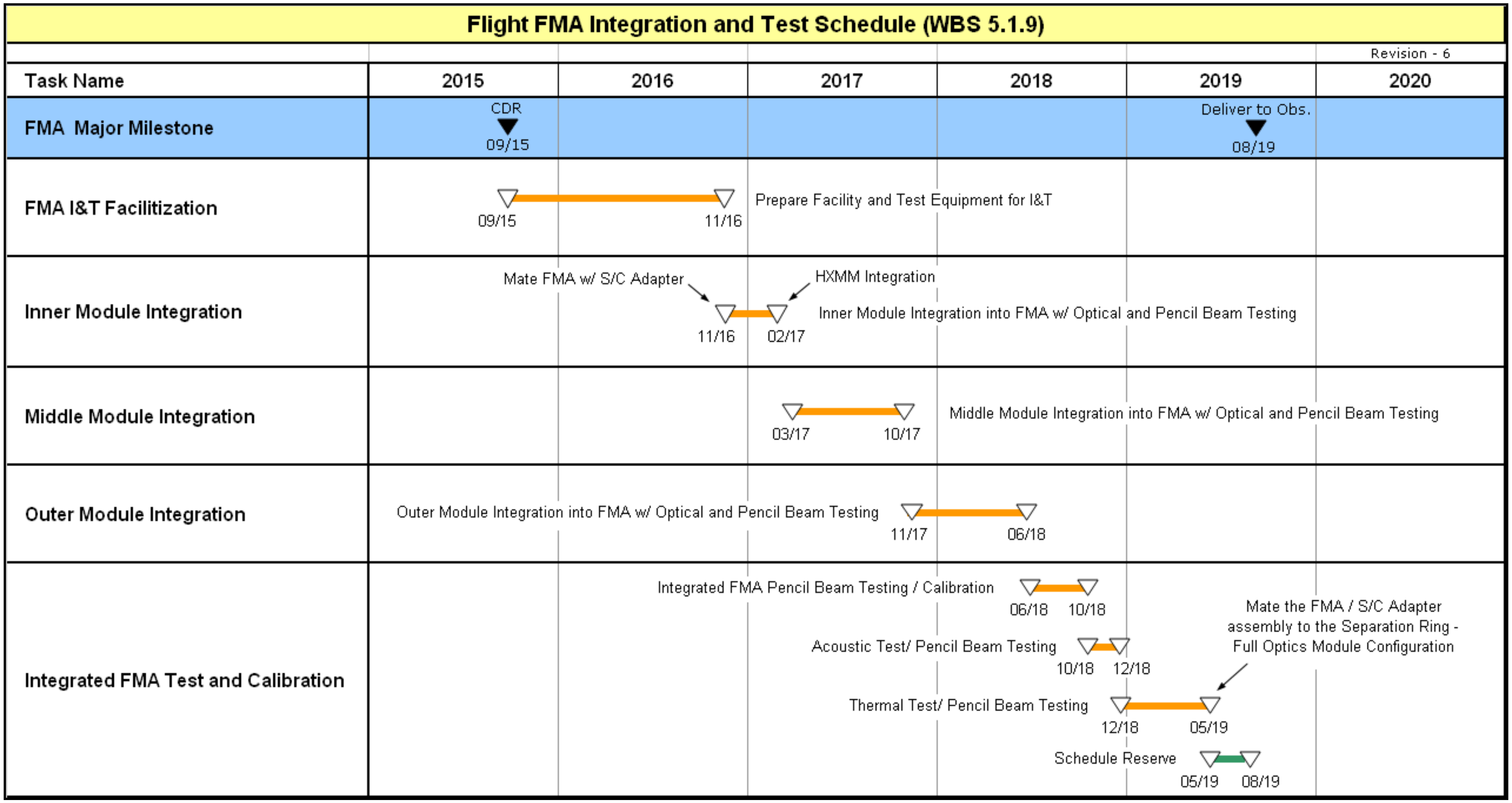
Production Rate of a Mirror Substrate Through the Temporary Bonding Process



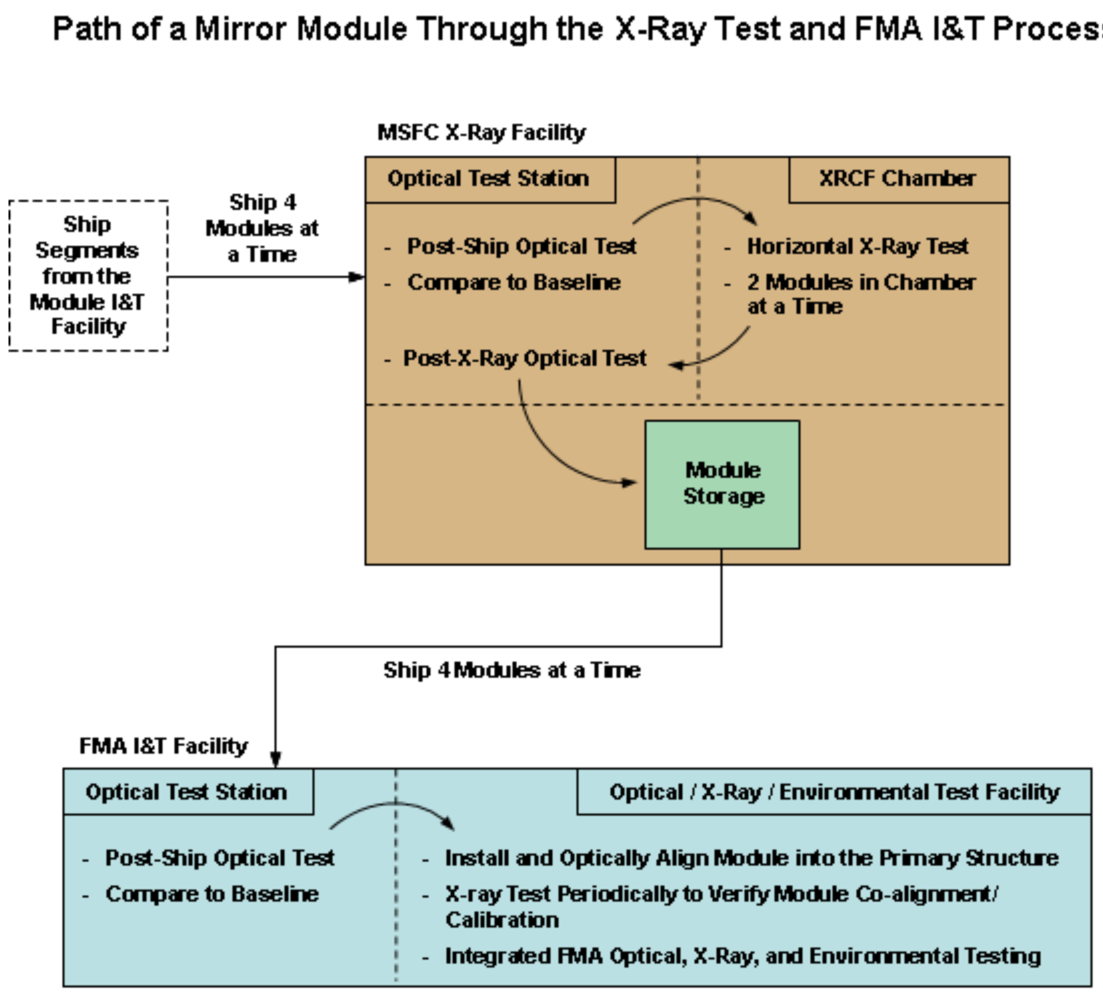
FMA Mirror Segment/Module Integration Flow



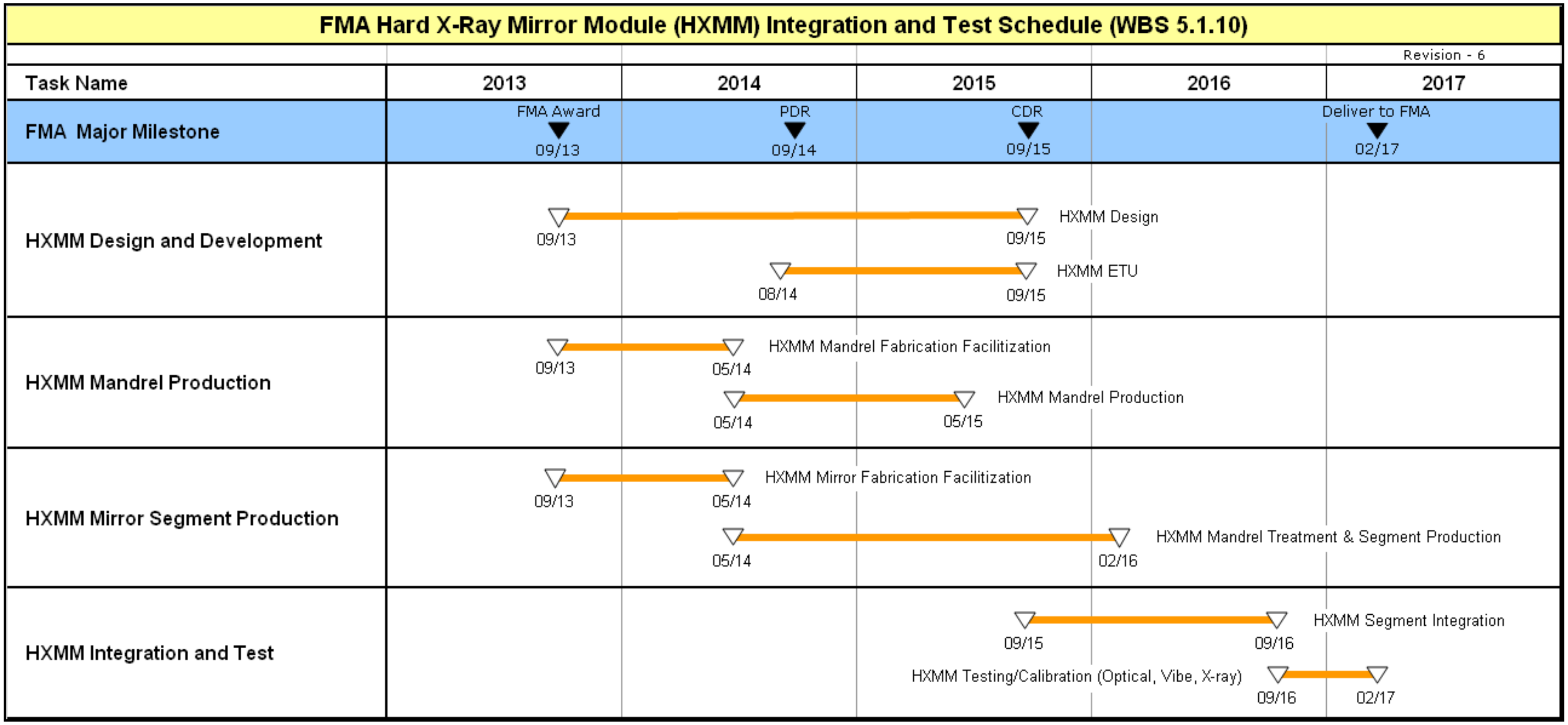
FMA Integration and Test Schedule



FMA Mirror Module Integration Flow



FMA Hard X-Ray Mirror Module Schedule



FMA Basis of Estimate Overview

- Provides ground rules and assumptions, data, environment, and events that underlie the cost estimated.
- The FMA estimate is based on a primary design and recent GSFC's NuSTAR mirror production experience.
- Using grassroots methodology, a team of experienced scientists and engineers estimated the effort required to design, build, integrate and test, and deliver the FMA.
- The BOE assumes off-site design, build, and qualification of the FMA and its components.
- The estimate reflects off-site contractor rates and fees, and includes management at the vendor site. This estimate does not include management and oversight by the IXO project (CS labor).
- The FMA cost includes management; systems engineering; safety and mission assurance; mandrel production, qualification, and shipping; mirror segment production, qualification, inspection, and shipping; primary and module structure design, build, test, and qualification; thermal system design and implementation; mirror module integration and test; and FMA integration and test. Travel, computer cost, shipping and all other support costs are included.

FMA Basis of Estimate Details

- The Soft X-ray Telescope (SXT) Mandrel Production cost assumes 52 sq-meters ($2M/sq-meter) of total area for 722 mandrels. The mandrel cost is based on actual costs for earlier Con-X / IXO mirror fabrication in 2000, and has been adjusted for inflation and tighter figure requirements. The 52 sq-meters area estimate accommodates 42 sq-meters actually needed, plus an additional 10 sq-meters (20 %) for edge-effects. The mandrel estimate is full-cost, including all labor and materials.
- The SXT Mirror Segment cost is based on NuSTAR mirror segment production experience required to slump glass sheets on mandrels to produce ~14,000 slumped glass segments. This estimate includes 10% mirror segment spares and provides a 45% contingency covering mirror segment breakage and the slumping process yield. 44 ovens, 4 cutting stations ($50K/station), 4 coating chambers ($500K/chamber), and 10 metrology stations ($1M/station) are required to produce mirror segments. Total output for all 44 ovens is 264 substrates per week. The glass cutting station, coating chamber, and metrology station capacities are sized to ≥ 12% above the mirror segment production rate. 12 slumping and 4 support technicians are assigned for the 44 ovens, and have been staggered to be compatible with the mirror production and process schedule.

FMA Basis of Estimate Details (cont'd)

- **The FMA Primary Structure estimate leveraged GSFC's Solar Dynamics Observatory (SDO) structure development cost and experience. The primary structure cost includes building and testing small-scale ETU's and a qualification unit. The SXT Module Structure cost includes building and tesing two module ETU's (inner and outer modules), and three qualification units (inner, middle, and outer modules).**
- **The SXT Module I&T cost covers the integration of 14,000 mirror segments into the 60 mirror modules via 24 alignment stations ($1M/station), which verify the mirror segment alignment prior to bonding them into the module structure. Completed modules will be vibration tested (4 at a time) and X-ray tested (2 at a time) to verify performance. The X-ray test cost was estimated by MSFC at $75K/day (over 66 weeks) and includes labor and consumables.**
- **The Hard X-ray Mirror Module (HXMM) cost is based on GSFC's NuSTAR, factoring-in the better angular resolution requirement, slightly larger size, and 1 assembly vs. NuSTAR's 2 assemblies. The HXMM estimate is full-cost, including all labor and materials. X-ray testing costs for the HXMM are assumed to be $75K/day for 20 days.**

FMA Basis of Estimate Details (cont'd)

- FMA I&T cost covers the integration of the 60 SXT Modules and the HXMM into the FMA primary structure. Module integration is assumed to be perforned with the FMA optical axis vertical. The modules will be optically tested as they are integrated to perform alignment, then subsequent X-ray tests (twice per ring) will be performed to calibrate and verify point spread function (PSF). X-ray testing will be repeated for the fully-integrated FMA. Environmental testing of the FMA as a unit will follow. The FMA cost also includes management, systems engineering, and safety and mission assurance. Travel, computer cost, ground support equipment, shipping, and all other support costs are also included.